https://ntrs.nasa.gov/search.jsp?R=19810013004 2020-03-21T13:24:58+00:00Z

N81-21533

DOE/NASA/0089-80/1
NASA CR-165144

STUDY OF FUEL CELL ON-SITE, INTEGRATED ENERGY SYSTEMS IN RESIDENTIAL/COMMERCIAL APPLICATIONS

R.A. Wakefield, S. Karamchetty, R.H. Rand,
W.S. Ku, and V. Tekumalla
Mathtech, Inc.
With Subcontractors:
The Ballinger Company, and
Public Service Electric and Gas Company

October 1980

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Under Contract DEN 3-89

for
U.S. DEPARTMENT OF ENERGY
Fossil Energy
Office of Coal Utilization

DEC 1980
RECEIVED
NASA STI FACILITY
ACCESS DEPT.

NOTICE

This report was prepared to document work sponsored by the United States Government. Neither the United States nor its agent, the United States Department of Energy, nor any Federal employees, nor any of their contractors, sub-contractors or their employees makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product or process disclcsed, or represents that its use would not fringe private-ly owned rights.

DOE/NASA/0089-80/1
NASA CR-165144

STUDY OF FUEL CELL ON-SITE, INTEGRATED ENERGY SYSTEMS IN RESIDENTIAL/COMMERCIAL APPLICATIONS

R.A. Wakefield, S. Karamchetty, R.H. Rand
W.S. Ku, and V. Tekumalla
MATHTECH, Incorporated
Arlington, Virginia 22209

With Sub-Contractors:
The Ballinger Company, and
Public Service Electric and Gas Company

October 1980

Prepared for
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135
Under Contract DEN 3-89

for
U.S. DEPARTMENT OF ENERGY
Fossil Energy
Office of Coal Utilization
Washington, D.C. 20545
Under Interagency Agreement DE-AI-03-ET-11272

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

ACKNOWLEDGEMENTS

The authors of this report would like to acknowledge the contributions of a number of persons to the work reported here. First, Mr. Robert Ciliano, Director of Energy Studies at MATHTECH, is acknowledged for his valuable guidance and administrative supervision of this study. The support of the MATHTECH personnel, including N.R. Friedman, W. Hery, V.L. Beach, and N. Okonkwo, also is acknowledged.

In addition to the principal investigators at Ballinger and Public Service Electric and Gas Company (PSE&G), we acknowledge the technical contributions of S. Darr and Craig Bernecker at Ballinger, and D. Sobieski and T. Piascik at PSE&G. Support to Ballinger in loads analysis was provided by Vinokur-Pace Engineering Services, Incorporated.

Finally, Gary Bollenbacher and Steve Simons of NASA Lewis Research Center are acknowledged for their technical direction and substantive contributions to this study effort.

EXECUTIVE SUMMARY

S.1 Introduction

Over the past ten years, fuel cells have received increasing consideration as a potential stand-alone or grid-connected energy source for residential and commercial buildings. They are especially well-suited for such applications, because of their environmental acceptability, high electrical efficiencies, and adaptability to heat recovery. Recent studies by the Department of Energy [1,2] and the Electric Power Research Institute [3] have concluded that there is a significant market for such applications and that fuel cells can make a valuable contribution in reducing building energy use. In this study, previous assessments are carried one step further by

- comparing the performance of more than one fuel cell design in each application considered
- evaluating fuel cell performance against that of realistic conventional energy systems, specified and costed by an established architect and engineering firm
- requiring that all on-site, fuel cell systems provide electric service at a reliability equivalent to that of a typical electric utility.

The objective of the study is to provide a quantitative basis for setting fuel cell cost and performance goals by evaluating the economic and technical performance of three phosphoric acid fuel cell types as applied in on-site, integrated energy system (OS/IES) to satisfy the energy needs of residential and commercial buildings. The technical performance and cost of each fuel cell type was specified by NASA Lewis Research Center (NASA-LeRC). The following four tasks were accomplished in completing this evaluation:

Task 1 - Application Selection and Characterization

This task included the selection and characterization of three residential/commercial applications, selection of three geographic locations, and estimation of building end use energy loads.

Task 2 - Energy System Design

Two conventional energy systems and three fuel cell integrated energy systems were designed for each building in each location. The conventional systems included an all-electric system and a gas/electric system. Each fuel cell integrated energy system design included one of the three fuel cell types under study and various types of supplementary HVAC equipment configured so as to meet various required design goals, including utility-level reliability. Part-load efficiencies of the fuel cells and some other HVAC equipment items were accounted for in evaluating alternative designs. Each fuel cell OS/IES design subsequently was modified to take advantage of the alternative assumption of operation with a utility tie-in.

Task 3 - Cost Estimates

Three categories of costs were estimated, including: installed capital costs, annual operating and maintenance costs, and annual energy costs. Installed capital costs were estimated to an accuracy of plus or minus 20%, and unit energy costs were based on DOE projections for 1985.

Task 4 - Economic Analysis

Levelized annual costs were calculated for each conventional and fuel cell energy system. These costs included fixed charges, purchased power costs, gas costs, operating and maintenance expenses and local taxes and insurance.

S.2 Application Characteristics and Selected Sites

Residential/commercial applications, representative buildings, and three alternate sites were selected, then building end-use, and energy requirements were estimated for each building/location combination. Three applications were selected to provide electric power requirements that ranged from 70Kw to 1.4Mw and energy use characteristics that imposed a range of design requirements. In addition, each of the three applications was required to constitute:

- a significant fraction of all residential/commercial energy consumers
- an economically and technically feasible application for a fuel cell integrated energy system
- a potentially significant market for fuel cell application.

The applications that were selected to satisfy these criteria were:

- low-rise apartment building
- retail store
- hospital

A single building design was selected to represent each of these generic applications. The three buildings were selected to comply with ASHRAE Standard 90-75 and to present a range of demand loads on the fuel cells under study. In addition, it was required that the designs be appropriate and reasonable for the three study locations. The selected designs were based on three existing buildings whose characteristics are summarized in Table S-1. As the table shows, demand loads for the three buildings range from approximately 100kW to 1MW. Where necessary, these selected designs were modified somewhat to conform to ASHRAE Standard 90-75.

Three geographic locations were selected that represent a range of the climatic conditions experienced by major segments of the U. S. population. The locations that were selected include:

- Chicago, Illinois
- Washington, D.C.
- Dallas, Texas

Hourly, daily, and annual energy requirements were estimated by end-use for each building in each location. The end-uses considered included electricity, space heating, space cooling, domestic hot water heating, cooking, and process heating (for hospital only). The AXCESS

TABLE S-1

SUMMARY CHARACTERIZATION OF SELECTED BUILDINGS

	Multi-Family Residential	Retail Store	Hospital
● Identification	Sodders Road Apts. New Jersey	Sears Roebuck Poughkeepsie, NY	Good Samaritan Hospital Lebanon, Pennsylvania
● Description	2-story, 24-unit wood/brick	1-story steel/brick	6-story concrete/brick
● Total Gross Area, M^2	1,904	10,420	11,043
● Connected Load,* KW	Not Available	988	1,800
● Demand Load,* KW	112	800	900
● Conventional Systems			
- All-Electricity			
heating	Air-Air Heat Pump	Air-Air Heat Pump	Water-Air Heat Pump
cooling	Air-Air Heat Pump	Air-Air Heat Pump	Water-Air Heat Pump
DHW	Electric Resistance Heater	Electric Resistance Heater	Reject Heat
- Gas-Electricity			
heating	Gas Air Furnace	Gas-Hot Water	Gas Steam
cooling	Electric Compression	Centrifugal Chiller	Steam Absorption
DHW	Gas	Gas	Steam HX
● Year Built	1975	1972	1971

(all upgraded to ASHRAE 90-75 for study.)

* For actual building.

building loads analysis program, developed and owned by the Edison Electric Institute, was used to develop these estimates. Major inputs to the AXCESS program included building design characteristics, operating profiles, and ASHRAE Test Reference Year (TRY) weather data for each geographic location.

The AXCESS program was used to provide hourly, monthly, and annual estimates of building end-use energy requirements for every fifth day of the typical (TRY) weather years. An annual breakdown of end-use requirements by application and location is presented in Figure S-1.

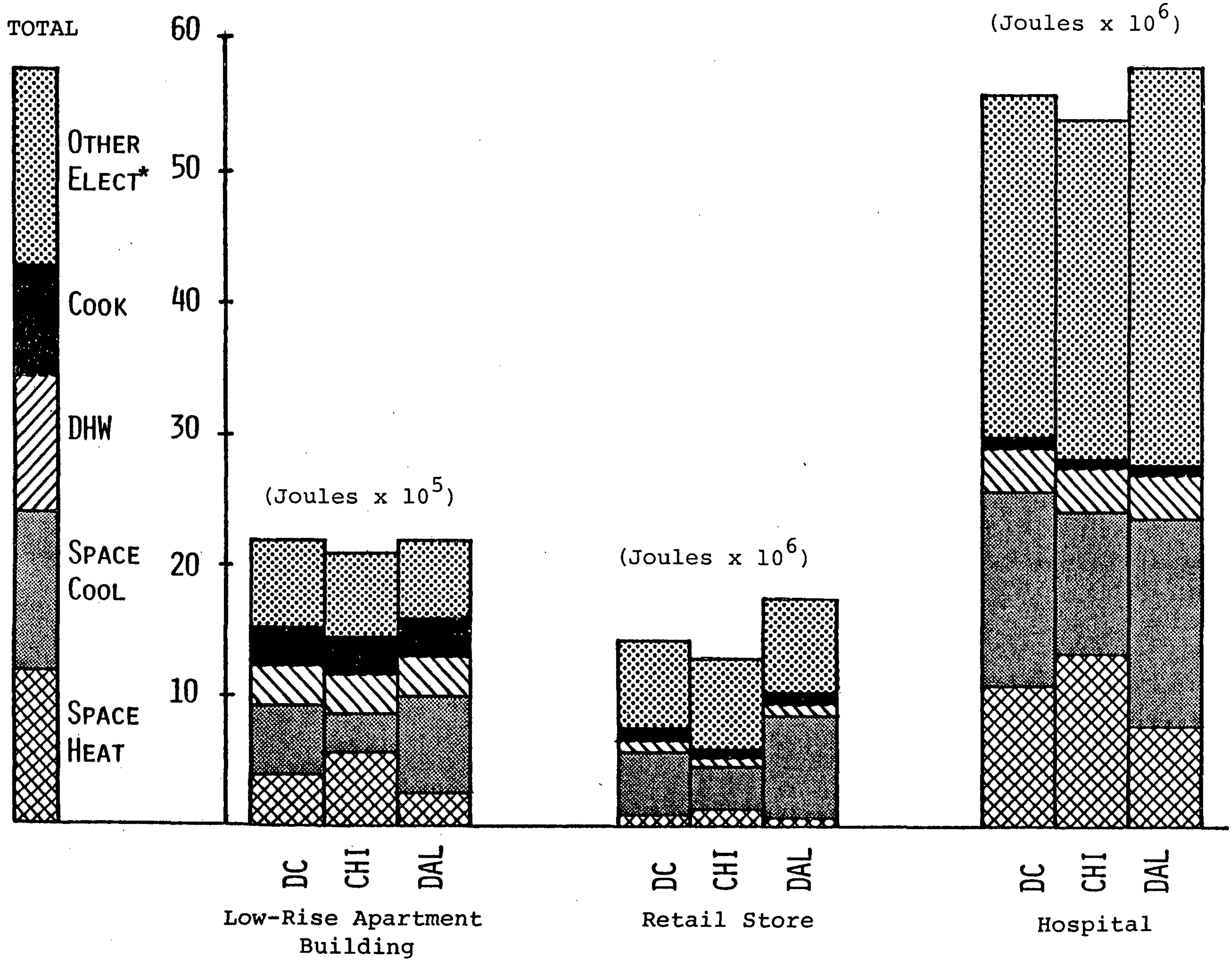
S.3 Energy System Design

S.3.1 Conventional Systems

All-electric and gas/electric conventional energy systems were designed for each building in each location so as to satisfy the following criteria:

- design and size using standard ASHRAE procedures
- conform to requirements of ASHRAE Standard 90-75
- for all-electric system, satisfy all energy needs with purchased electricity
- for gas/electric system, maximize use of purchased gas.

These systems were designed and sized by professional building HVAC and electrical engineers at the Ballinger Company in Philadelphia, Pennsylvania, following the same practices that would be used if the systems were actually going to be built. System equipment was specified in commercially available sizes, and electrical and thermal schematics were produced. Table S-2 provides a summary listing of



* Includes all end-uses that can be met only with electricity.

Figure S-1. AXCESS Analysis of Annual Building End-Use Energy Demands

TABLE S-2

SUMMARY OF CONVENTIONAL SYSTEM DESIGNS - WASHINGTON, D.C.

APPLICATION	CONVENTIONAL SYSTEM	
	ALL-ELECTRIC	GAS/ELECTRIC
Low-Rise Apartment Building	• 24 Air-to-Air Split System Heat Pumps @7.04 kW_t, with supplementary electric heating @2.55 kW_e.	• 24 Gas-Fired Air Furnaces, With Dx Cooling and Remote Condensors.
Retail Store	• 15 Air-to-Air Package Rooftop Heat Pumps @88.0 kW_t, With Supplementary Electric Heating @33.5 kW_e.	• 1 Electric Centrifugal Chiller @1267 kW_t • 1 Cooling Tower @1267 kW_t • 1 Gas-Fired Boiler @308 kW_t • 12 Rooftop Air Handlers, With Tempering Coils, @3.97 m^3/sec
Hospital	• 13 Water-to-Air Heat Pumps @141 kW_t, Roof-Mounted • 15 Water-to-Air Heat Pumps With Horizontal Coiling @14.1 kW_t • 1 Closed Circuit Evaporative Cooler @2036 kW_t	• 1 Absorption Chiller @2036 kW_t • 1 Cooling Tower @2036 kW_t • 3 Gas-Fired Steam Boilers @3129 kg/hr • 6 Air Handling Units, @1.35 to 10.84 m^3/sec

major conventional system equipment items for the Washington, D.C. location. As the list indicates, centralized systems were chosen for the store and hospital and a unitary system for the apartment building.

S.3.2 Fuel Cell Systems (Without) Utility Tie-In

Fuel cell, on-site, integrated energy systems were designed for each of three fuel cell types for each building in each location. The design guidelines were as follows:

- maximize use of fuel cell reject heat
- minimize energy system life cycle cost
- provide electric service reliability equivalent to typical utility
- consider use of various types of supplemental HVAC equipment

Operating characteristics of the three fuel cell types were specified by NASA. All three are phosphoric acid fuel cells that may be characterized as follows:

- Type A - Present Generation Fuel Cell
- Type B - Advanced Technology Fuel Cell
- Type C - Near Term Technology Fuel Cell

The Type A and Type C fuel cell power plants are representative of those being developed for commercialization in the 1985 time frame. The type B fuel cell power plant represents a significant technology advance over the other two types. Figure S-2 shows the electrical and thermal efficiencies versus operating level for each of the three fuel cell types.

Figure S-3 illustrates the overall design process that was utilized in defining the fuel cell integrated energy systems. As the figure shows, the process consisted of four basic steps. First, a generalized system configuration was defined (shown in Figure S-4),

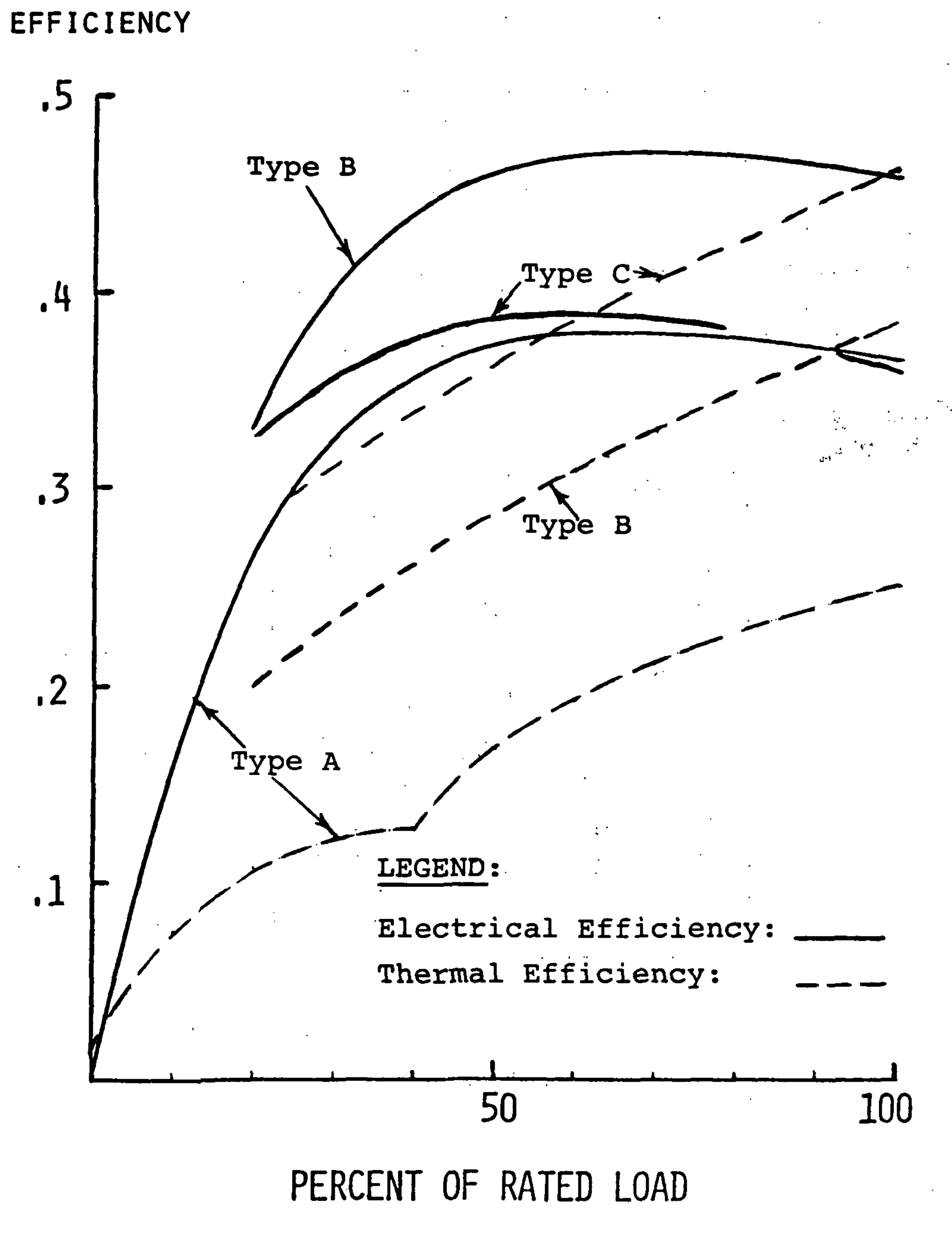


Figure S-2. Electrical and Thermal Efficiency of Three Fuel Cell Types.

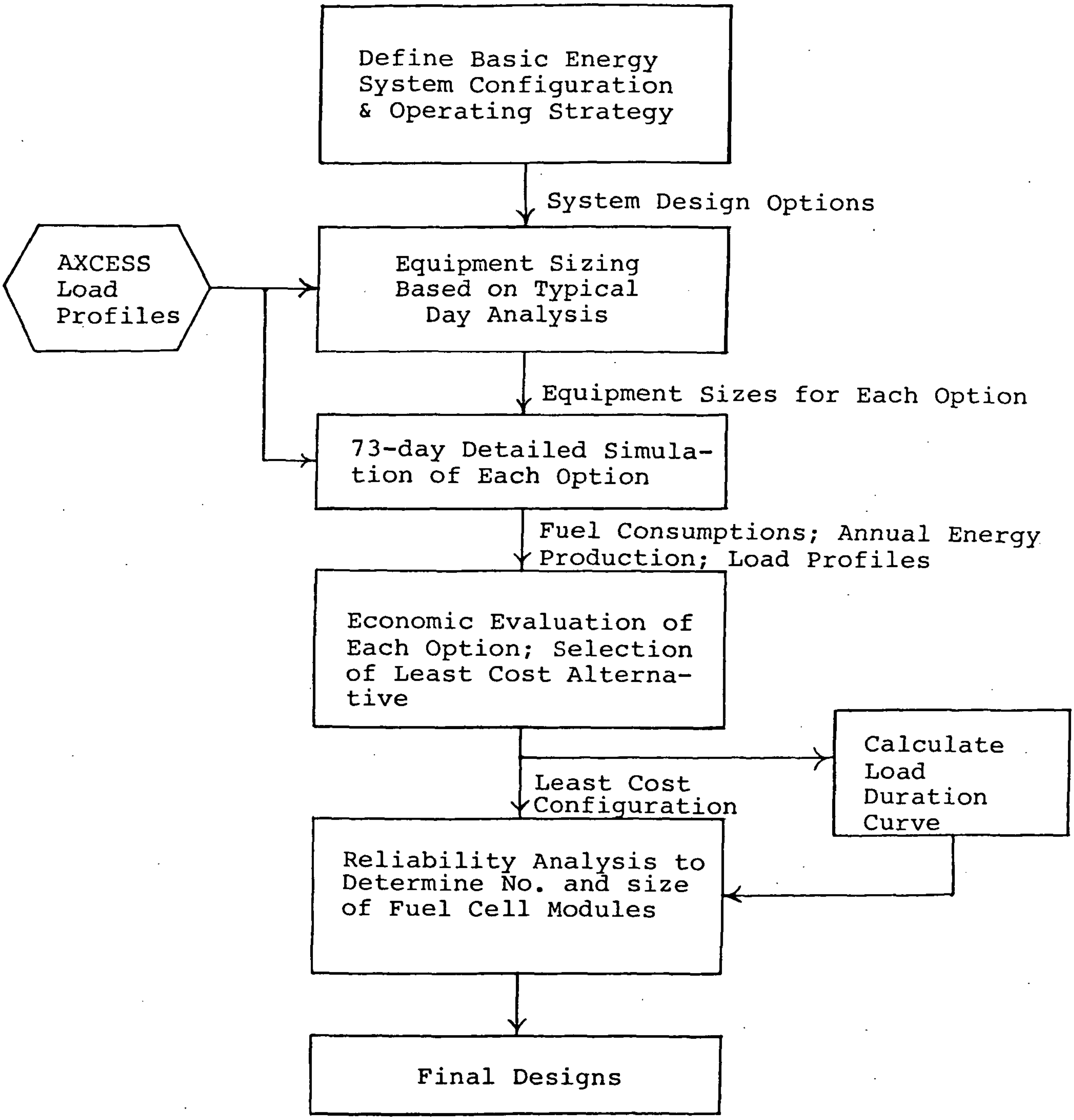


Figure S-3. Design/Simulation Approach for OS/IES Without Utility Tie-In.

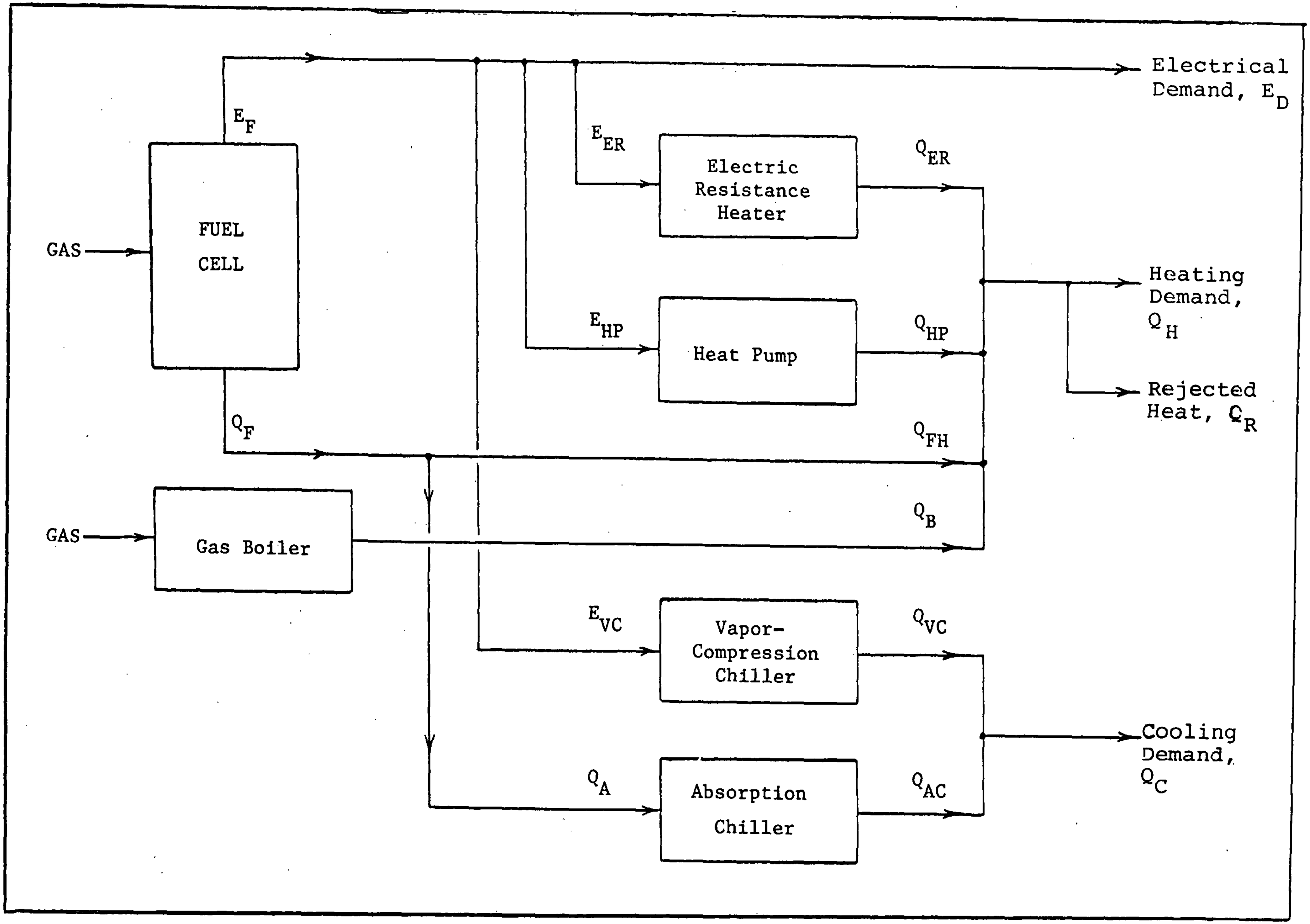


Figure S-4. Generalized System Block Diagram and operating guidelines were established to conform to the design criteria presented above. Then, for each building in each location a number of alternate equipment sizings were considered, and a final size set was selected based on approximate economic and thermal evaluations of each alternative for four typical days. (Fuel cell modularity and reliability was not considered at this stage of the design process.) Using the above design sizes, each fuel cell system was then subjected to a detailed 73-day simulation to determine system performance over a typical weather year. Finally, system reliability was assessed in order to determine the optimum number and size of fuel cell modules needed to provide electric service reliability equivalent to a typical utility.

Fuel cell system reliability was assessed by Public Service Electric and Gas Company, Newark, New Jersey, against that normally provided by electric and gas utilities. Each system was designed to have a "loss of energy probability" of 99.98%. The number and size of fuel cell modules required to accomplish this were selected so as to minimize installed fuel cell capital cost. Each fuel cell module was assumed to have a forced outage rate of 3%. The optimum module sizes and numbers of modules for each fuel cell system are listed in Table S-3.

Once the reliability analysis was accomplished, final design specifications were made and system schematics were completed. Table S-4 shows the final fuel cell and HVAC equipment sizes for each application in Washington, D.C. Design sizes varied only slightly for the other two locations.

S.3.3 Fuel Cell Systems with Utility Tie-In, No Sales

In order to evaluate the costs and benefits of maintaining a back-up connection between the on-site system and an electric utility,

TABLE S-3

OPTIMUM MODULE SIZE AND NUMBER OF MODULES FOR FUEL CELL SYSTEM WITHOUT UTILITY TIE-IN

BUILDING	LOCATION	FUEL CELL TYPE	MODULE SIZE (KW)	NUMBER of MODULES	TOTAL FUEL CELL CAPACITY (KW)	PERCENT RESERVE
Low-Rise Apartment	Chicago	A	6	12	72	20
		B	6	12	72	20
		C	6	12	72	20
	Dallas	A	6	12	72	20
		B	6	12	72	20
		C	6	12	72	20
	Washington, DC	A	6	12	72	20
		B	6	12	72	20
		C	6	12	72	20
Retail Store	Chicago	A	60	12	720	15
		B	55	13	715	14
		C	67	11	737	17
	Dallas	A	61	12	732	19
		B	61	12	732	18
		C	48	15	720	13
	Washington, DC	A	67	11	737	18
		B	61	12	732	17
		C	56	13	728	15
Hospital	Chicago	A	120	11	1320	18
		B	100	14	1400	17
		C	120	11	1320	18
	Dallas	A	100	14	1400	17
		B	140	10	1400	17
		C	140	10	1400	22
	Washington, DC	A	130	11	1430	19
		B	100	14	1400	17
		C	130	11	1430	19

TABLE S-4

OS/IES DESIGN SIZES VS. APPLICATION (VALUES FOR WASHINGTON, D.C. - FUEL CELL TYPE B)

Equipment Item	Residential		Retail Store		Hospital	
	Size	L.F.(%)	Size	L.F.(%)	Size	L.F.(%)
Fuel Cell, kW_e	72	65	720	35	1430	72
Heat Pump, kW_t	29.3	5.6	87.9	3.5	263.7	16.4
V.C. Chiller, kW_t	70.4	59.8	352	63.4	352	130.2
ABS Chiller, kW_t	105.6	38.7	880	38.7	1408	77.4
E.R. Heater, kW_e	20	0.34	40	1.3	70	34
Boiler, kW_t	73.2	2.9	805.8	1.3	1238	4.1

the above designs were modified so as to reduce the total fuel cell capacity and number of modules and take advantage of a certain amount of utility backup power. In this case, the objective was to minimize the sum of the annualized installed, fuel cell capital cost and the annual cost of utility backup. Table S-5 shows the fuel cell module sizes and numbers of modules that were used in this assessment.

S.3.4 Fuel Cell Systems with Power Sales to the Utility

This was purely an economic assessment. The fuel cell integrated energy system designs were the same as for the case without utility tie-in. In other words, the on-site systems were not assumed to buy power from the utility but only to sell excess power to the utility.

S.4 Economic Assessment

S.4.1 Methodology

The economics of the conventional and fuel cell systems for each building in each location were evaluated using a standard, levelized annual cost methodology, specified by NASA Lewis Research Center and similar to that developed by Phung [1]. The levelized annual cost approach, which is often employed by electric utilities, allows a comparison of the life cycle costs of investment alternatives in terms of an equivalent, constant, annual cost that includes a number of levelized components. In this, the levelized components included: fixed charges, purchased power costs, gas costs, operating and maintenance expenses, and insurance and local taxes. Calculation of these components required a number of general and "building specific" economic assumptions and data values, which are summarized in Table S-6.

S.4.2 Cost Estimates

Calculation of levelized annual costs required consistent

TABLE S-5

OPTIMUM MODULE CONFIGURATION AND UTILITY BACKUP REQUIRED FOR FUEL CELL SYSTEM WITH UTILITY TIE-IN

(Washington, D. C., Location)

BUILDING	FUEL CELL TYPE	MODULE SIZE, kW	NUMBER OF MODULES	TOTAL FUEL CELL CAPACITY, kW	BACKUP POWER REQUIRED, kW	ANNUAL ENERGY SUPPLIED BY UTILITY, kWh
Low-Rise Apartment	A	10	6	60	10	3,442
	B	6	10	60	6	3,358
	C	6	10	60	6	3,610
Retail Store	A	52	12	624	52	12,788
	B	85	8	680	85	4,591
	C	117	6	702	117	5,128
Hospital	A	100	12	1,200	100	35,511
	B	100	12	1,200	100	37,059
	C	100	12	1,200	100	31,812

TABLE S-6

ECONOMIC ASSUMPTIONS AND DATA

GENERAL:

- Constant Dollar Analysis Zero Inflation
- Energy System Purchased as Part of Overall Building
- Investment Tax Credit Not Applicable
- 25-Year System Life
- Straight-Line Depreciation

BUILDING SPECIFIC:	Residential	Store	Hospital
• Ownership And Financing Assumed	Direct Ownership	Limited Partnership	Non-Profit Corporation
• Cost of Debt	4.2	3.7	1.3
• Debt of Common Equity	1.9	2.8	1.9
• Debt/Equity Ratio	4	3	3
• Building Design and Construction Time, Years	3	3.5	4
• Electricity Price (1978 $/kWh)	.042	.042	.042
• Annual Escalation	0.7%	0.8%	0.8%
• Gas Price (1978 $\$/10^6$kJ)	3.66	3.19	2.3%
• Annual Escalation	2.1%	2.3%	2.3%
• Federal Income Tax Rate	42%	45%	0%
• Rate For Insurance and Local Income Taxes	3.5%	3.5%	0.5%

estimates of the capital, energy, and operating and maintenance costs of each conventional and fuel cell energy system. System capital costs were estimated by Ballinger. Since the objective was to identify those costs which varied between alternative systems, the scope of these estimates was limited to those portions of building energy conversion and distribution systems that vary with the system selected. Fuel cell purchase costs were specified by NASA, and all other equipment costs were specified by Means [2] or, quotations by manufacturers and distributors. Costs for fuel cell system installation and interface were estimated by Ballinger. Figures S-5 through S-7 show the total estimated capital costs for the apartment building, store, and hospital, respectively, by energy system and location. In most cases, fuel cell system capital costs are 2 to 4 times higher than those for their conventional alternatives. However, the capital cost of the fuel cell powerplant itself accounts for only about 30% of the total capital cost of most fuel cell integrated energy systems.

A number of energy cost assumptions were required including electricity and gas prices for 1985, costs for utility backup power and rates for the sale of excess fuel cell electricity to the utility. The sources of these estimates and the values assumed are shown in Table S-7.

Operating and maintenance (O & M) cost estimates were based on the assumption listed in Table S-8. The fuel cell O & M rate of 6 mills/kWh was specified by NASA LeRC. Cost assumptions for the conventional equipment were based on estimates by various commercial equipment maintenance contractors, but because of the wide variance between these estimates a significant amount of engineering judgment was required.

S.5 Study Results

Study results included levelized annual costs and annual energy

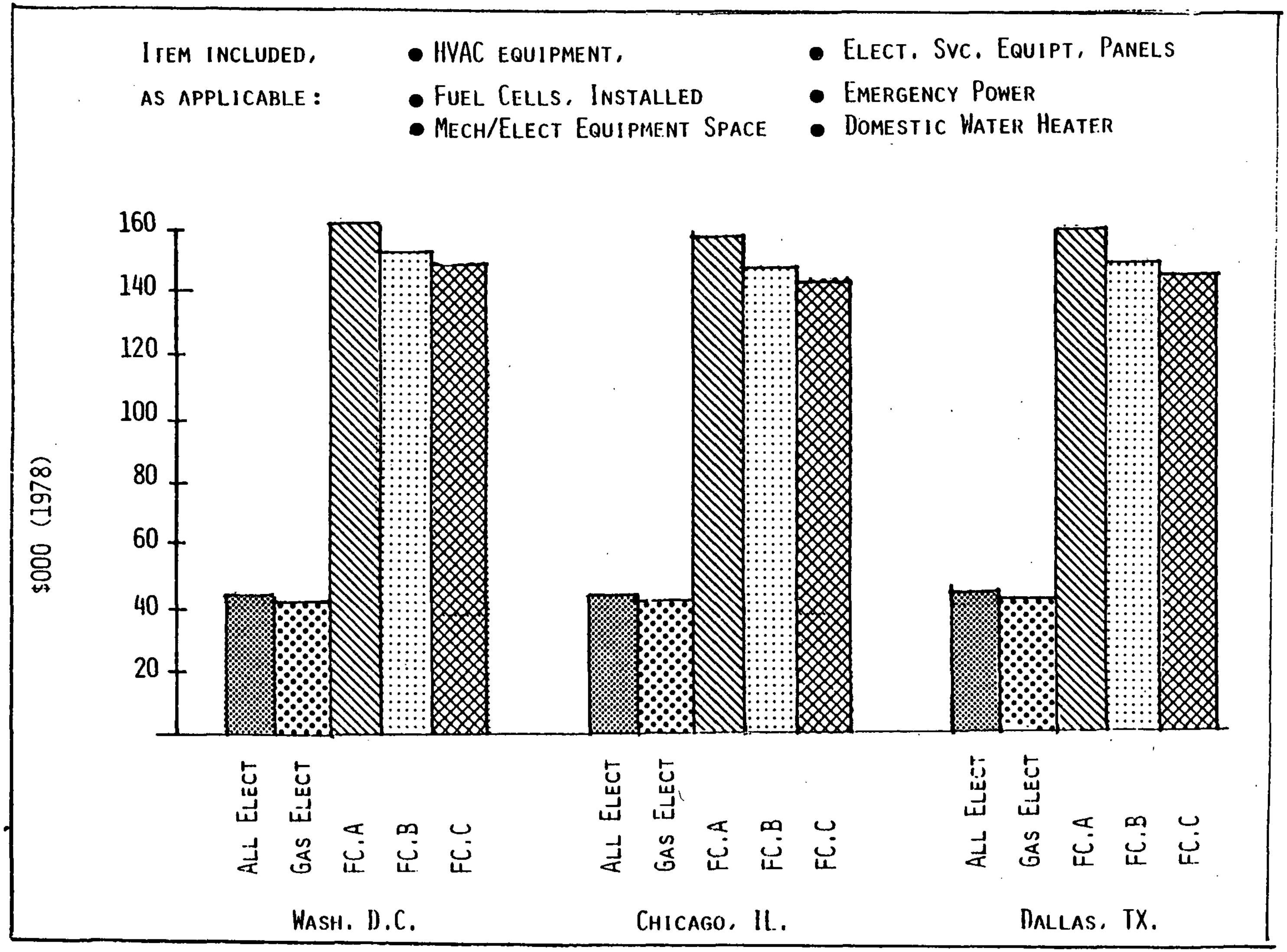


Figure S-5. Capital Cost Summary: Low-Rise Apartment Building

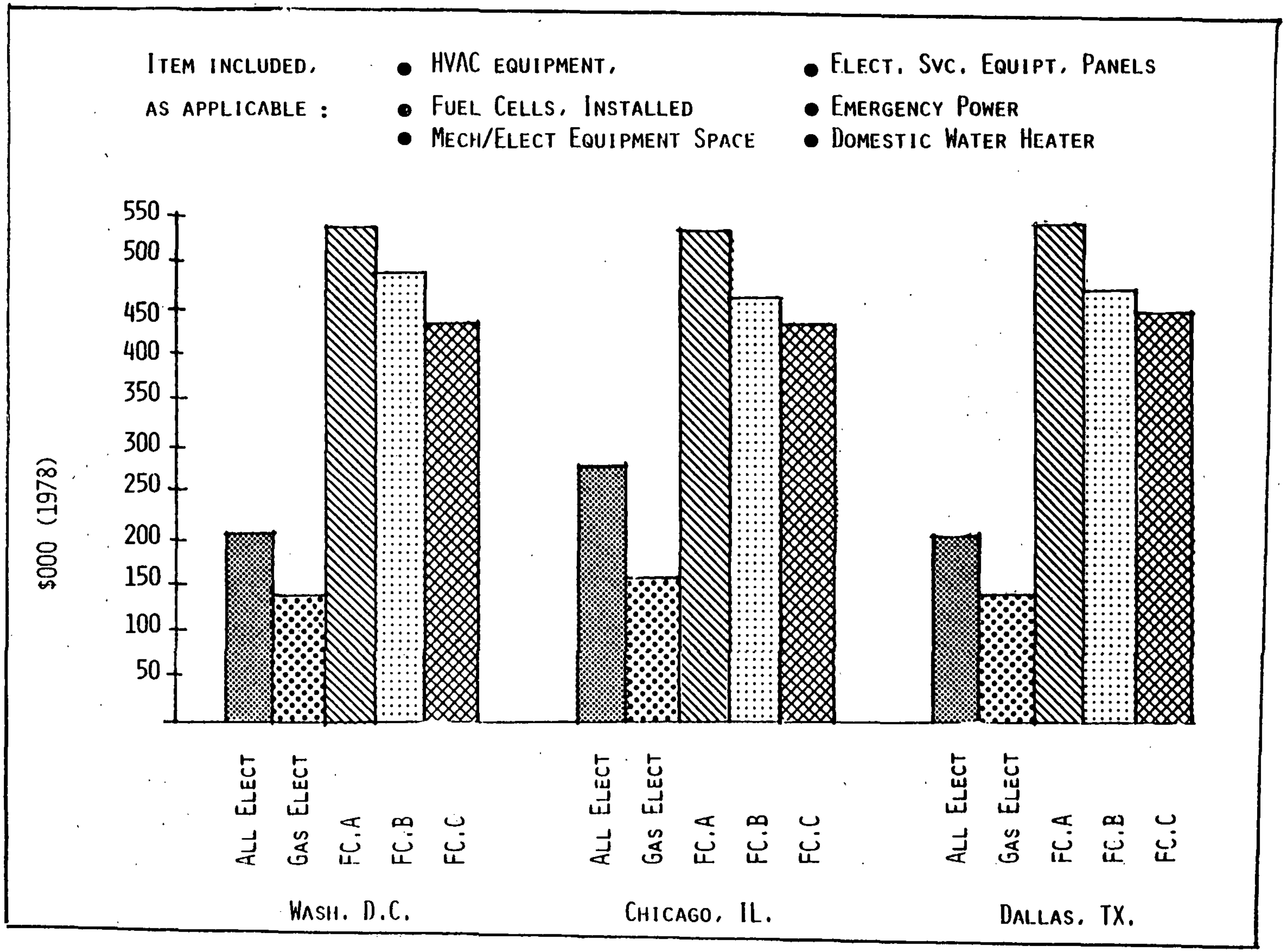


Figure S-6. Capital Cost Summary: Retail Store

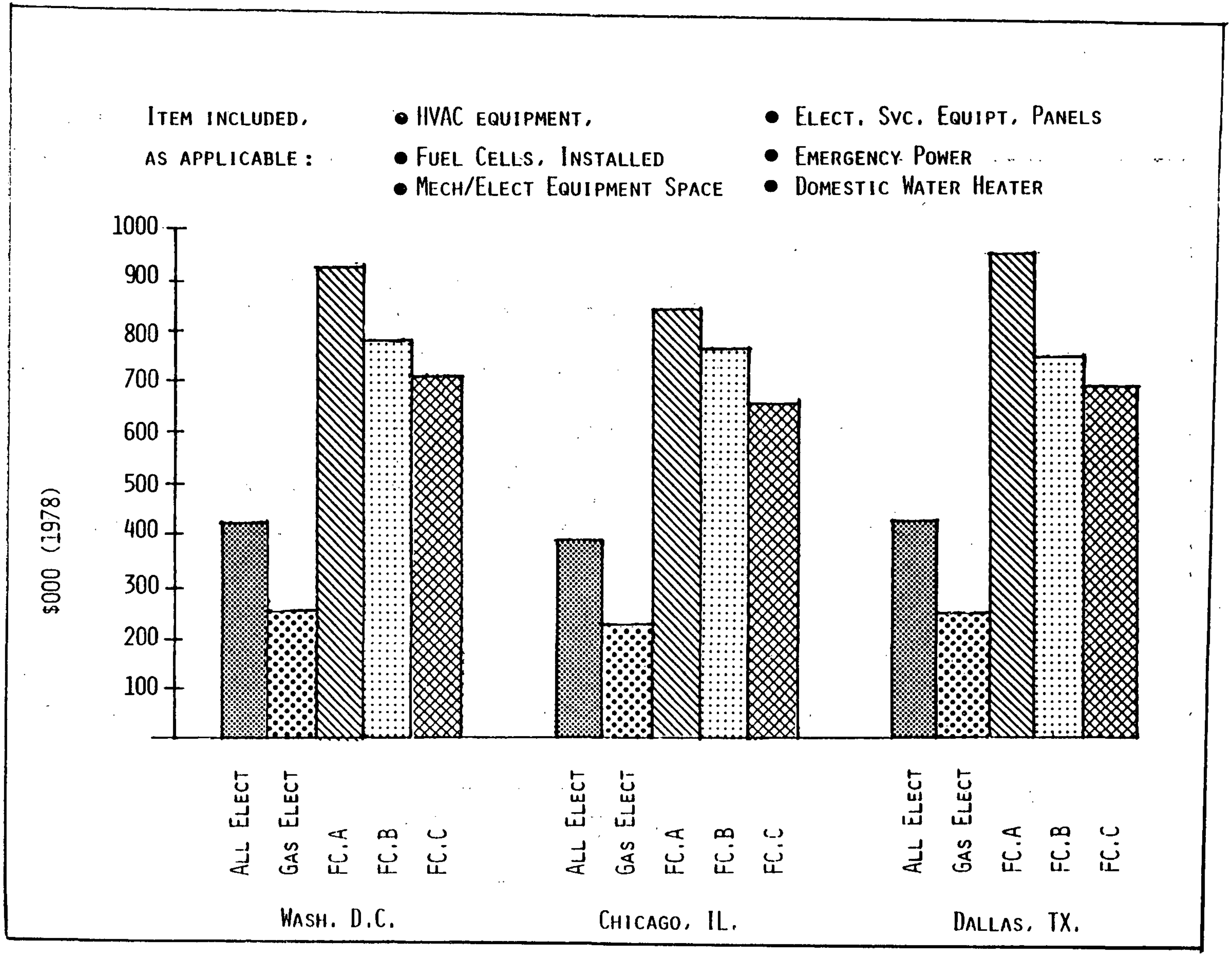


Figure S-7. Capital Cost Summary: Hospital

TABLE S-7

ENERGY COST ASSUMPTIONS

- **BASE ENERGY PRICES** - USED EIA PROJECTIONS FOR 1985, ASSUMING MEDIUM ENERGY SUPPLY/DEMAND, OIL PRICE OF 15.00 $/BBL

	ELECTRICITY (MILLS/KWH)	GAS ($/$10^6$BTU)
• RESIDENTIAL PRICE:	41.9	3.47
• COMMERCIAL PRICE:	41.8	3.02

- **STANDBY RATES** - BASED ON PG&E'S S-1 RATE SCHEDULE FOR COGENERATION FACILITIES
  - STANDBY CHARGE: $1.00/kW/MO.
  - POWER PURCHASES: (DURING OUTAGES) $4.00/kW/MO. DEMAND CHARGE; 33.0 MILLS/KWH ENERGY CHARGE

- **BUY-BACK RATES** - BASED ON ELECTRIC UTILITY ON- AND OFF-PEAK INCREMENTAL ENERGY COSTS
  - ON-PEAK INC. COST: 28.7 MILLS/KWH
  - OFF-PEAK INC. COST: 20.1 MILLS/KWH

NOTE: All costs in 1978 dollars.

TABLE S-8

ANNUAL OPERATING AND MAINTENANCE COST ASSUMPTIONS

Equipment Item*	LOW-RISE APARTMENT BUILDING ENERGY SYSTEM			RETAIL STORE ENERGY SYSTEM			HOSPITAL ENERGY SYSTEM		
	All-Electric	Gas/Electric	OS/IES	All-Electric	Gas/Electric	OS/IES	All-Electric	Gas/Electric	OS/IES
Fuel Cell, \$/kWh	-	-	0.006	-	-	0.006	-	-	0.006
Heat Pump, \$/kW_t	11.4	-	11.4	11.4	-	11.4	11.4	-	11.4
Vapor Compression Chiller, \$/kW_t	-	18.8	18.8	-	6.25	6.25	-	-	6.25
Absorption Chiller, \$/kW_t	-	-	22.7	-	-	7.67	-	7.67	7.67
Boiler (or Furnace), \$/kW_t	-	3.41	3.41	-	3.41	1.70	1.70	1.02	1.36 1.70

* NOTE: Annual O&M costs for electric resistance heaters were assumed to be negligible in all cases.

consumptions for the five energy systems and applications in each geographic location. The major results are those for the case where no utility tie-in is assumed. These are presented first, followed by the results of various sensitivity investigations. Then the resulting costs and savings associated with utility backup and power sales to the utility are presented.

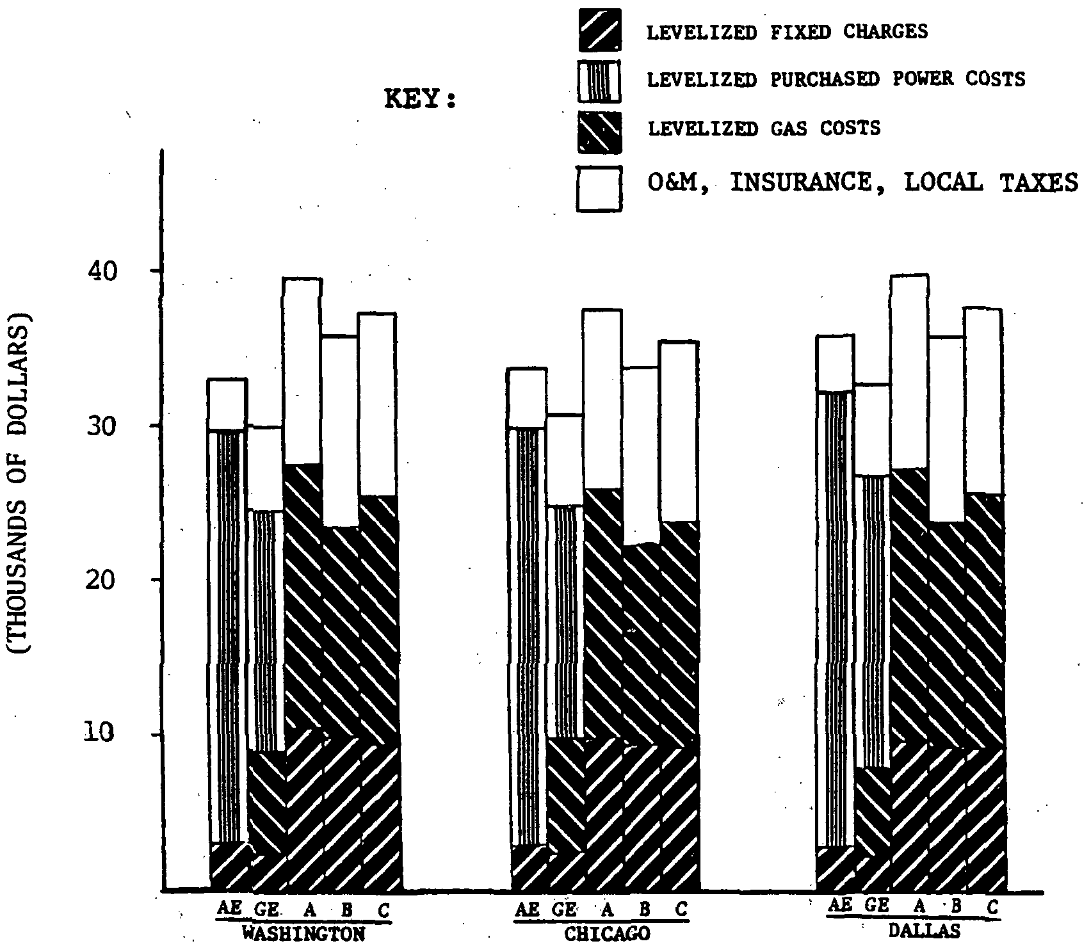
S.5.1 Base-Case Results

The "base case" results are those for the case where no utility tie-in is assumed. The economic results which are presented in Figures S-8 through S-10 are the result of the levelized annual cost analysis presented in the previous section. The annual energy consumption results, which are presented in Figures S-11 through S-13, were produced during the 73-day design phase simulation.

A brief examination of the economic results in Figures S-8 through S-10 indicates that fuel cell system life cycle costs are:

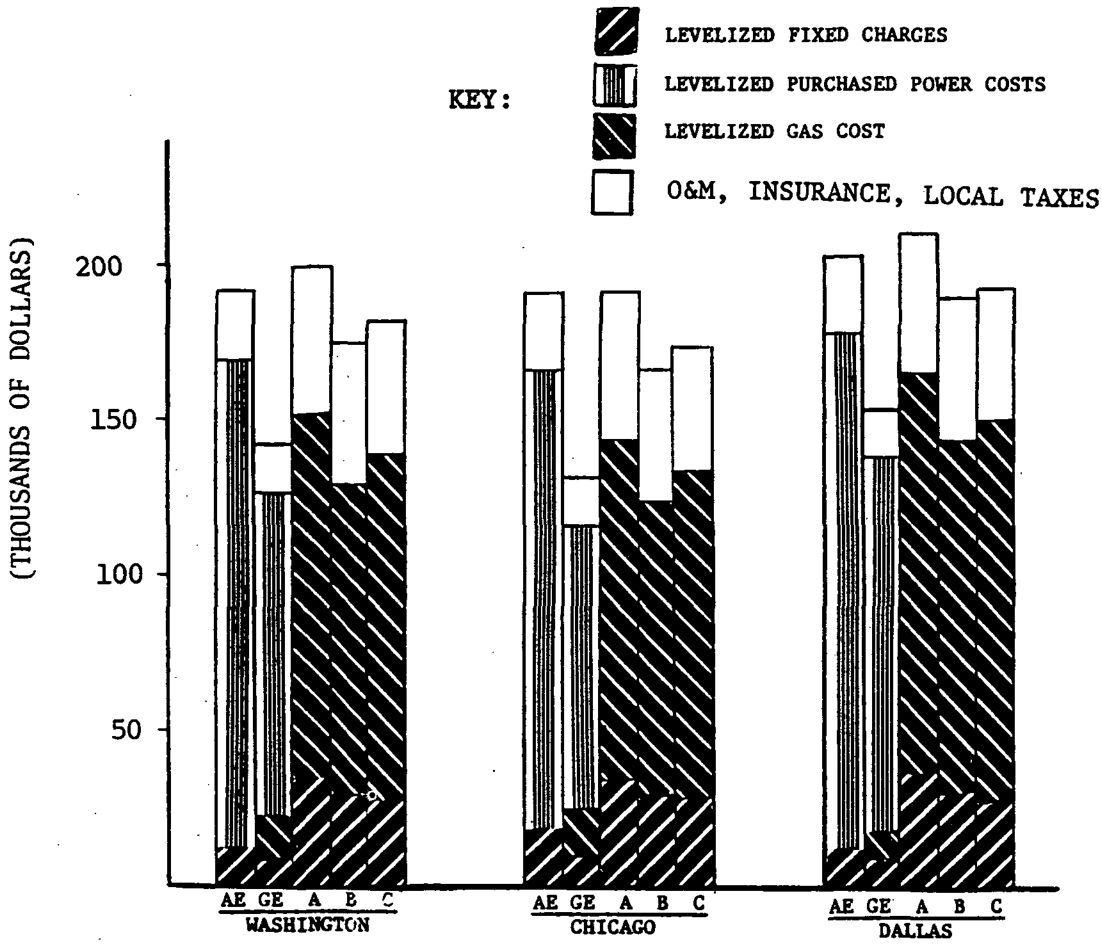
- 0% to 30% higher than those of conventional apartment building energy systems
- 13% lower to 26% higher than those of conventional store energy systems
- 5% to 49% lower than those of conventional hospital energy systems.

The principal reason for the relative unattractiveness of the fuel cell system results for apartment buildings is the fuel cell systems' high fixed and O & M costs that are not completely offset by the savings in energy costs. This same observation can be made for the retail store fuel cell systems when compared with the gas/electric system. However, all-electric system fixed and O & M costs for the store were higher relative to those of the fuel cell system, making the fuel cell system a little more attractive than the all-electric system in terms of total levelized annual cost. Finally, fuel cell system costs for the hospital are lower than either conventional



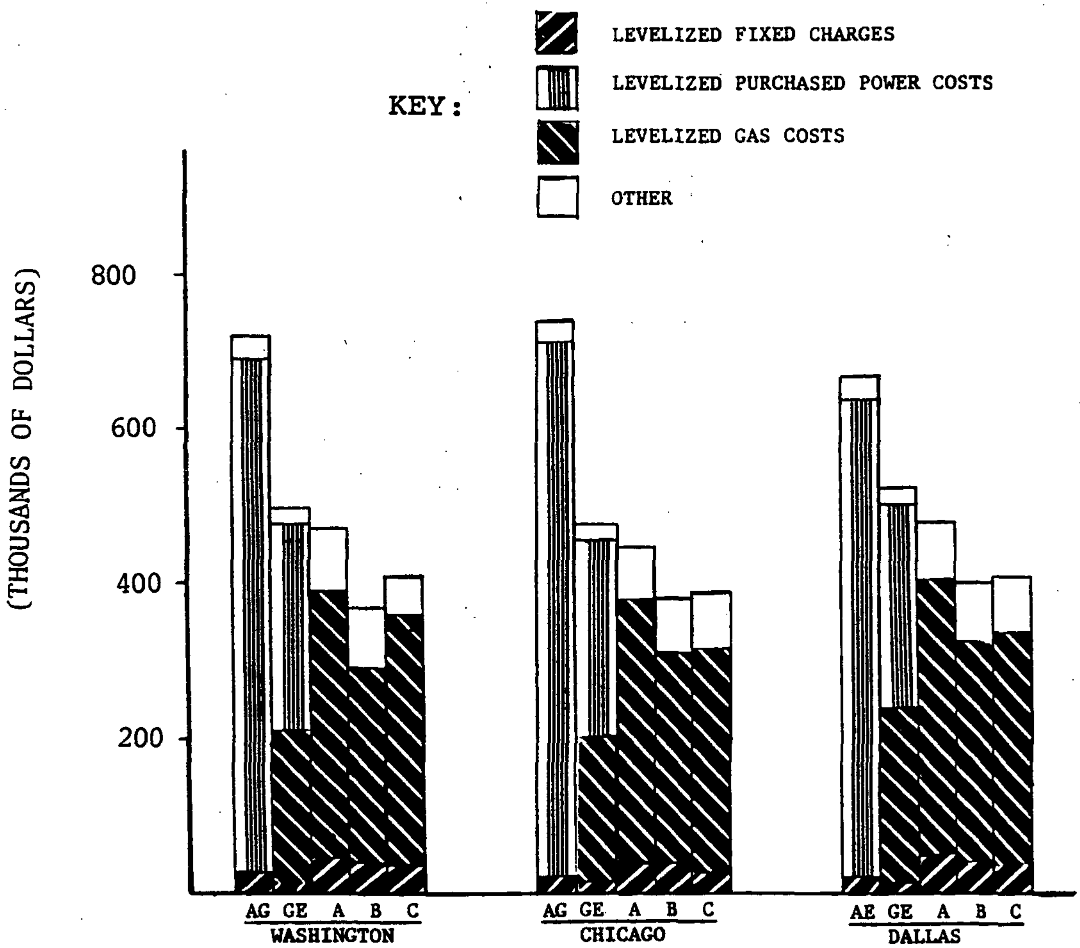
SYMBOLS: AE = All-Electric System
GE = Gas/Electric System
A = OS/IES With Type A Fuel Cell
B = OS/IES With Type B Fuel Cell
C = OS/IES With Type C Fuel Cell

FIGURE S-8 . Levelized Annual Cost: Residence



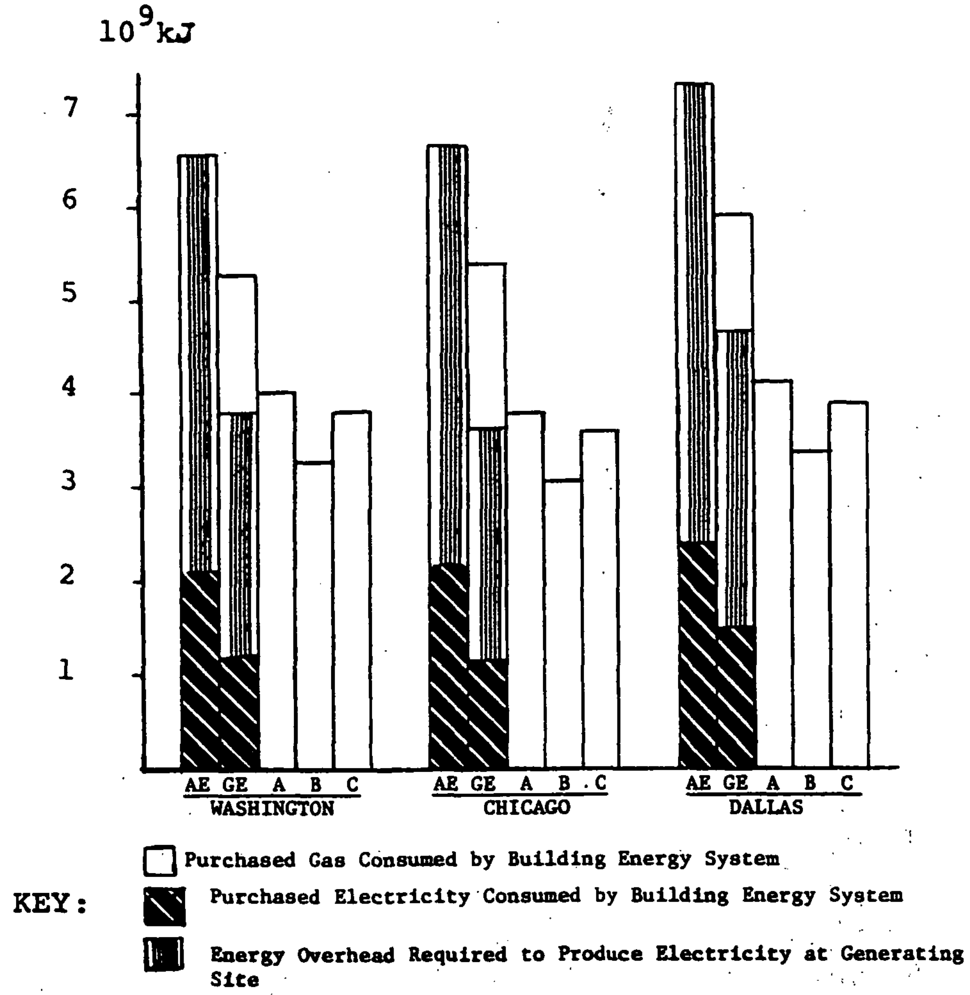
SYMBOLS: As Defined in Figure 6-1.

FIGURE S-9 . Levelized Annual Cost: Retail Store



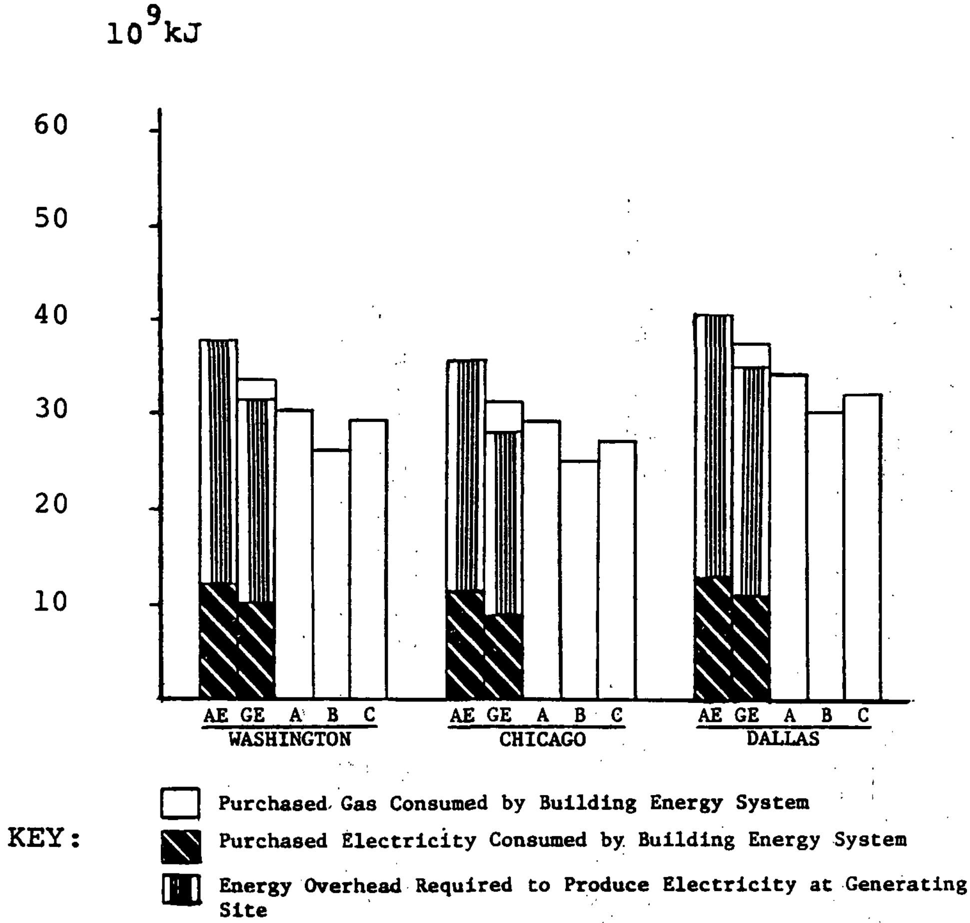
<u>SYMBOLS</u>: As Defined in Figure S-8.

FIGURE S-10 . Levelized Annual Cost: Hospital



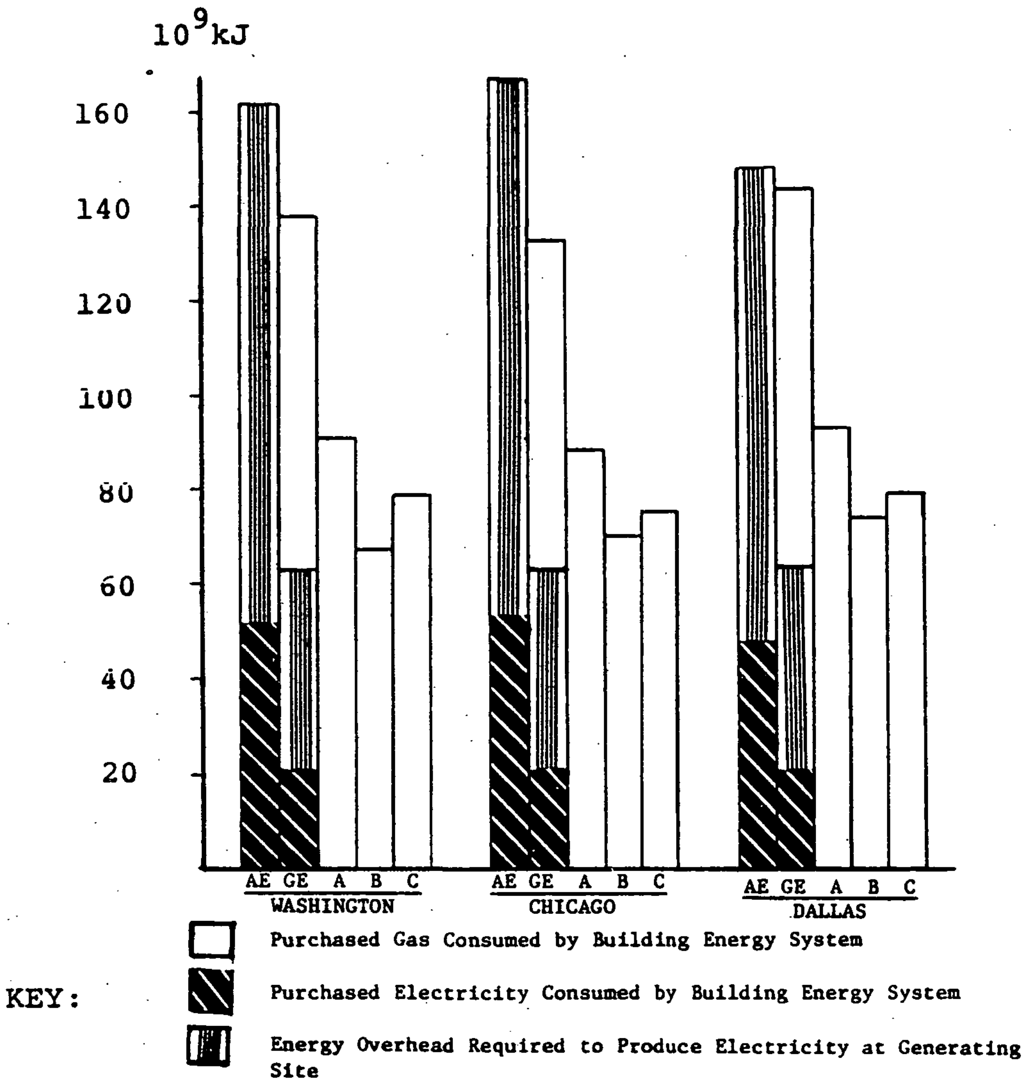
SYMBOLS: As Defined in Figure S-8.

FIGURE S-11. Annual Energy Consumption: Residence



SYMBOLS: As Defined in Figure S-8.

FIGURE S-12· Annual Energy Consumption: Retail Store



SYMBOLS: As Defined in Figure S-8.

FIGURE S-13. Annual Energy Consumption: Hospital system in every case, due to a dramatic increase in the relative importance of energy costs as a component of overall energy system life cycle costs. This increase is due to the high end-use load factors of the hospital. Geographic location has a relatively minor effect on the above economic results.

Similarly, the annual energy consumption results presented in Figures S-11 through S-13 indicate that fuel cell system energy resource consumptions are:

- 24% to 54% lower than those of conventional apartment building energy systems
- 8% to 31% lower than those of conventional store energy systems
- 35% to 58% lower than those of conventional hospital energy systems

These results include, and give equal weighting to, the total resources required at a central station powerplant to generate electricity for use at the building site. The primary reasons for the reduced energy savings of the fuel cell systems for the retail store are:

- the large fraction of the store's annual energy needs that are required for space cooling, which is supplied quite efficiently by conventional means
- the more efficient centralized conventional energy equipment used for the retail store

As for the economic results, geographic location does not tend to change the relative rankings of the five energy systems.

Relative rankings of the three fuel cell systems are the same for both economic and energy results. The rankings are influenced primarily by the higher cost and lower efficiency of the Type A fuel cell (for which higher return temperature was assumed), and the higher efficiency and moderate cost of the Type B fuel cell.

S.5.2 Sensitivity Results

A number of sensitivity analyses were made to determine the effects of changes in electricity and gas prices, fuel cell purchase costs, investment tax credits, and financing and ownership assumptions. The results, which are presented in Table S-9, show that variations in gas and electric prices will have the greatest effect on fuel cell system economic savings, ranging from 4% to 8%. The effects of a 10% investment tax credit for the fuel cell systems also were significant, causing life cycle costs for these systems to decrease by 1% to 4%. The costs and benefits of incorporating thermal storage in the on-site fuel systems also was investigated, but it was found that except for the apartment building systems, gas cost savings were too small to offset the increased capital costs. A small savings in levelized annual cost of approximately 1% would take place for the apartment building, with an attendant energy consumption savings of about 3.5%

S.5.3 Effect of Utility Back-Up and Power Sales to the Utility

The economic impact of reducing on-site system reserve capacity and maintaining a utility back-up and of selling excess fuel cell electricity to the utility backup were found to be surprisingly small, ranging from a maximum of 0.8% to a minimum of -0.3%. The primary reason for this is the relatively small percent reduction in on-site system fixed costs, coupled with the relatively high assumed backup rates.

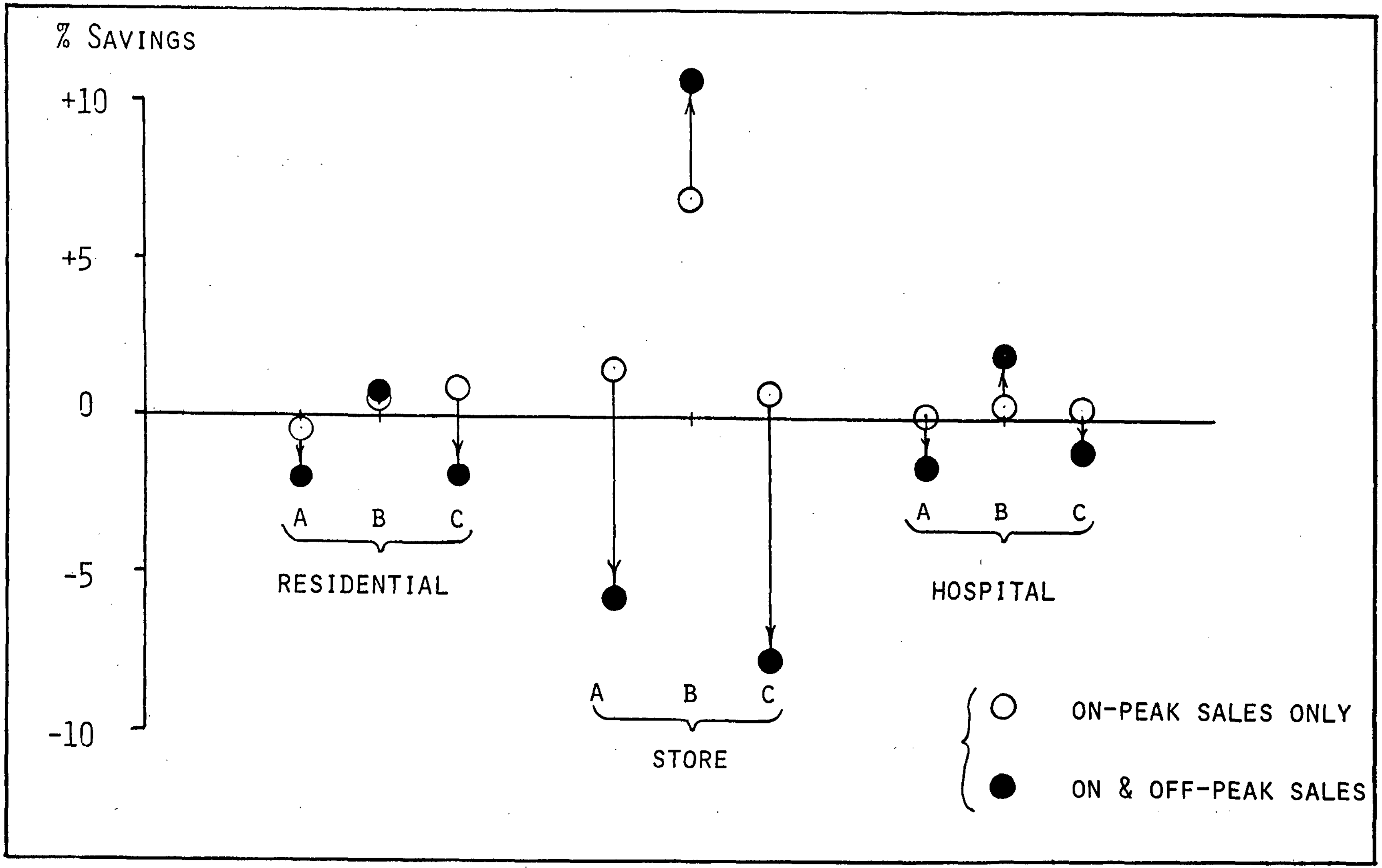
As Figure S-14 illustrates, the relative benefits of selling excess power to the utility were more encouraging, but only for the Type B fuel cell system in a retail store. Most of the fuel cell systems show a small cost savings of 1% or less for excess power sales during the utility's on-peak period with significant cost increases for combined on and off peak sales. The Type B fuel cell systems, however, shows increased savings when sales are made during

TABLE S-9

RESULTS OF SENSITIVITY STUDY

VARIABLE	PERCENT CHANGE IN LEVELIZED ANNUAL COSTS*		
	RESIDENTIAL	STORE	HOSPITAL
Electricity Price (+10%)			
• OS/IES	0	0	0
• All-Electric	8.1	8.2	10.7
• Gas/Electric	5.2	7.5	6.0
Gas Price (-10%)			
• OS/IES	-4.4	-6.2	-7.4
• All-Electric	0	0	0
• Gas/Electric	-2.1	-1.0	-4.1
Fuel Cell Purchase Credit (OS/IES only) (0 → 10%)	-0.47	-0.82	-0.53
Investment Tax Credit (OS/IES only) (0 → 10%)	-3.8	-2.4	-0.89
Alternate Ownership			
• OS/IES	-0.21	+1.4	---
• All-Electric	-0.23	+0.63	---
• Gas/Electric	-0.23	+0.25	---
(Type of Ownership)	(Limited Partnership)	(Corporation)	---

*All OS/IES results are for system with Type C fuel cell in Washington, D.C. location.



Figures S-14. Impact of Power Sales on Levelized Annual Costs both on and off peak periods. This is because of the lower incremental cost of power from the Type B fuel cell (due to its higher electrical efficiency). Economic savings for the Type B fuel cell system are quite significant (6% to 10%) for the retail store, due to its inherently lower annual load factors.

S.6 Conclusions

Based on the above results, the following conclusions are drawn:

- For the specific buildings studied, implementation of fuel cell OS/IES's would reduce apartment building and hospital energy consumption by 24% to 50%, while retail store energy consumption would be reduced by a lesser amount, from 6% to 30%.
- Fuel cell OS/IES's are economically attractive for the hospital, marginally attractive for the retail store, and generally unattractive for the low-rise apartment building.
- Fuel cell designs with high efficiency (electrical plus thermal), especially when operated at part-load, will be much more competitive with conventional energy systems.
- Geographic location has a modest effect on the above conclusions. For the apartment building and hospital, colder climates are more attractive because of the high efficiency of the on-site fuel cell systems in satisfying heating loads. Otherwise, the observed effects of changes in geographic location were inconclusive.
- For the specific systems considered and utility back-up costs assumed, the economic effects of utility back-up are negligible.
- Excess power sales to the utility will improve annual economics for OS/IES's that employ high efficiency fuel cells, especially for applications with low load factors.
- The relative economics of on-site fuel cell systems improve significantly with an increase in electricity price or a decrease in gas price.
- A large investment tax credit (of 10% or more) could encourage the use of on-site fuel cell systems.
- Thermal storage costs generally exceed the economic benefits, but the use of storage would reduce OS/IES annula gas consumption by 1% to 4%.

The above conclusions are made only for buildings studied. Results may differ for other builidngs of these types. Also, based on these results, relatively little can be said about other building types.

CHAPTER 1

INTRODUCTION

Because of their high efficiency, environmental acceptability, and heat recovery potential, fuel cells are presently being considered as a power source for building on-site, integrated energy systems. Most of the early investigations of such applications were associated with the TARGET (Team to Advance Research for Gas Energy Transformation) Program, jointly sponsored by United Technologies Corporation (UTC) and a consortium of gas and gas-electric utilities. Under this program, a 12.5 kW fuel cell power plant was developed, and approximately 60 such plants were field-tested in actual buildings. The results of these tests were sufficiently encouraging that the Department of Energy and the Gas Research Institute are now supporting the commercialization of a UTC-developed 40 kW fuel cell, specifically aimed at the building market. A recent study by Oak Ridge National Laboratory indicates that the potential market for such fuel cells may be as large as 3.4 million kW by 1985.

The study reported here differs in several respects from past investigations of fuel cell OS/IES in building applications. First, the study is not an evaluation of any specific fuel cell, but a comparative assessment of three alternative fuel cell designs. Second, the conventional building energy systems, against which the alternative fuel cells are evaluated, were specified by an architect and engineering firm that routinely designs such systems. Finally, in contrast to past studies, it was required that all on-site, fuel cell systems provide electric service at a reliability equivalent to that of an electric utility. Thus, every attempt has been made to specify realistic conventional building energy systems and to compare them with fuel cell on-site/integrated energy systems which provide comparable services and performance.

1.1 Objectives

The objective of this study is to evaluate and compare the economic and technical performance of three fuel cell types when employed in on-site, integrated energy systems (OS/IES) to supply electricity, heating, and cooling to residential and commercial buildings in a range of geographic locations. For the purposes of this study, an on-site, integrated energy system is defined as a system that provides electricity at the building site and includes the recovery of useful heat for space and water conditioning and process use. In each case, the performance of the fuel cell system is compared with that of conventional building energy systems which provide the same services. The study results will provide NASA and the Department of Energy with information that may be used in setting cost and performance goals for developmental phosphoric acid fuel cells.

1.2 Scope

The scope of this study effort is best summarized by the following descriptions of the tasks that were accomplished:

Task 1 -- Application Selection and Characterization

In Task 1, residential/commercial applications, typical buildings and locations were selected, and a building energy loads analysis program was chosen and utilized to estimate hourly end-use energy loads for each building. First, three residential/commercial applications were selected with electric power requirements in the range of 10 kW to 1 Mw, and with energy use characteristics that impose a range of design requirements on the on-site fuel cell system. Three typical buildings, based on real building designs, were then selected and characterized to serve as a consistent data base for further analysis. Each building design either already conformed to, or was modified to conform to, ASHRAE Standard 90-75, as applied to 1978 construction. Three geographic locations were selected that represent a range of environmental conditions in areas of the continental United States occupied by major segments of the national population.

Major building energy loads analysis programs, capable of analyzing multi-zone buildings in different geographic locations, were identified and reviewed. Then one program was selected and used to analyze the three selected buildings in each of three geographic locations.

Task 2 -- Energy System Design

For each building/location combination, two conventional building energy systems and a number of on-site fuel cell systems were designed. Both the conventional and fuel cell systems were designed so as to minimize life cycle costs. The conventional systems included an all-electric system, for which all energy demands were met with electricity from an electric utility, and a gas and electric system, for which end-use demands were satisfied by gas to the maximum extent possible. The two systems were specified thus so as to cover the likely extremes in conventional energy system designs for the applications selected.

On-site fuel cell systems were designed to maximize the utilization of thermal and electric energy produced by the fuel cell, while minimizing system life cycle costs. Designs were developed for each building and each location, first assuming no connection (or tie-in) with the electric utility, and then assuming such a tie-in but with no power sales to the utility. In one location, the benefits of power sales to the utility were evaluated for each of the three applications. All fuel cell systems which did not assume a utility tie-in were designed to supply building electricity with a reliability equivalent to that provided by a typical electric utility.

Task 3 -- Cost Estimates

Estimates of installed capital costs, annual operating and maintenance expenses, and annual energy costs were developed for each of the Task 2 energy system designs and reported in 1978 dollars. Installed capital costs were estimated for each major equipment item to an accuracy of $\pm$ 20%. Annual operating and maintenance expenses included both labor and parts for routine maintenance, and repair and replacement. Energy costs were calculated for each system based on:

i) system annual gas and electricity consumptions;

ii) published projections of gas and electricity prices for the year 1985; and

iii) assumed constant gas and electric escalation rates over the system life.

Estimates were also made of the cost of utility standby service and the rates that an electric utility would pay in purchasing electricity from a fuel cell OS/IES.

Task 4 -- Economic Analysis

Levelized annual costs were calculated for each conventional and fuel cell energy system. These costs included the following levelized components: fixed charges, purchased power costs, gas costs, operating and maintenance expenses, and insurance and local taxes. The financial and economic data and ownership assumptions for each application were applied uniformly to all energy systems. An analysis subsequently was conducted of the sensitivity of these economic results to changes in fuel and purchased electric power costs, changes in fuel cell capital costs, and alternative energy system ownership assumptions.

Based on the relative economic and technical performance levels achieved by the above conventional and fuel cell energy systems, conclusions are drawn regarding the relative merits of the three fuel cells under study, and fuel cell commercialization is discussed in light of recent and possible future public policy actions.

1.3 Groundrules

- All energy systems considered are assumed to be new installations; retrofit applications were not considered.
- Private or coporate ownership is assumed for all conventional and fuel cell energy systems considered.
- All buildings analyzed are assumed to conform to ASHRAE Standard 90-75 as applied to 1978 construction.
- The conventional energy systems considered in this study are typical of those presently being specified for the building types under consideration.
- All fuel cell systems which do not include a utility tie-in are designed to provide building electric service with a reliability equivalent to that of a typical electric utility.
- For the fuel cell systems which include a utility tie-in, it is assumed that the on-site system purchases electric power from the utility only during periods when one or more fuel cell module is experiencing an unscheduled outage and the remaining modules are unable to satisfy the load.

- It is assumed that all fuel cell systems will be comprised of at least two stand-alone modules and that all scheduled fuel cell maintenance will take place at times when the remaining fuel cell modules can satisfactorily meet the entire building energy load.

- The performance, costs and operating characteristics of the three fuel cell types considered were supplied by NASA Lewis Research Center, and these characteristics are summarized in Appendix A.

CHAPTER 2

SELECTION AND CHARACTERIZATION OF RESIDENTIAL/COMMERCIAL APPLICATIONS

The first task of the study was to select three residential/ commercial applications, a representative building design for each application, and three geographic locations, and to estimate the hourly end-use energy loads for each building/location combination. The selected applications include:

- multi-family, low-rise apartment building
- retail store
- hospital.

The building designs that were selected to represent these applications are summarized in Table 2-1.

The selected geographic locations include:

- Washington, D. C.
- Chicago, Illinois
- Dallas, Texas.

This chapter discusses the rationale for these selections, characterizes the selected buildings and locations in more detail, and discusses the estimation of building end-use energy loads.

2.1 Selection of Generic Applications

In order to assess the feasibility of fuel cell on-site integrated energy systems for residential/commercial applications, three building types were selected to best satisfy the following criteria:

- The application should be a significant energy consumer in the R/C sector

TABLE 2-1

SUMMARY CHARACTERIZATION OF SELECTED BUILDINGS

	Multi-Family Residential	Retail Store	Hospital
● Identification	Sodders Road Apts. New Jersey	Sears Roebuck Poughkeepsie, NY	Good Samaritan Hospital Lebanon, Pennsylvania
● Description	2-story, 24-unit wood/brick	1-story steel/brick	6-story concrete/brick
● Total Gross Area, M^2	1,904	10,420	11,043
● Connected Load,* KW	Not Available	988	1,800
● Demand Load,* KW	112	800	900
● Conventional Systems			
- All-Electricity			
heating	Air-Air Heat Pump	Air-Air Heat Pump	Water-Air Heat Pump
cooling	Air-Air Heat Pump	Air-Air Heat Pump	Water-Air Heat Pump
DHW	Electric Resistance Heater	Electric Resistance Heater	Reject Heat
- Gas-Electricity			
heating	Gas Air Furnace	Gas-Hot Water	Gas Steam
cooling	Electric Compression	Centrifugal Chiller	Steam Absorption
DHW	Gas	Gas	Steam HX
● Year Built	1975	1972	1971
(all upgraded to ASHRAE 90-75 for study.)			

* For actual building.

- A typical establishment representing the application should have electric power requirements in the range of 10 kW to 1 MW.
- A fuel cell system should be technically feasible and economically competitive for the building type.
- The three building types selected should impose a range of design requirements on the fuel cell power system including different load profiles, thermal-to-electric ratios, capacities, etc.
- Each of the three applications selected should constitute a potentially significant market for fuel cell power systems.

The following section discusses the process and rationale for these selections.

2.1.1 Selection Process

Four residential and ten non-residential applications were considered in a two-step selection process, as illustrated in Figure 2-1. In the first step these applications were screened in terms of:

- their significance as future energy consumer in the R/C sector
- typical peak electrical power requirements
- thermal/electric demand ratios

Those applications which passed the above screens were then assessed to determine:

- thermal and electric load factor desirability
- availability of quality data
- existence of a range of design requirements in the final selections.

The following discussion explains these steps in more detail.

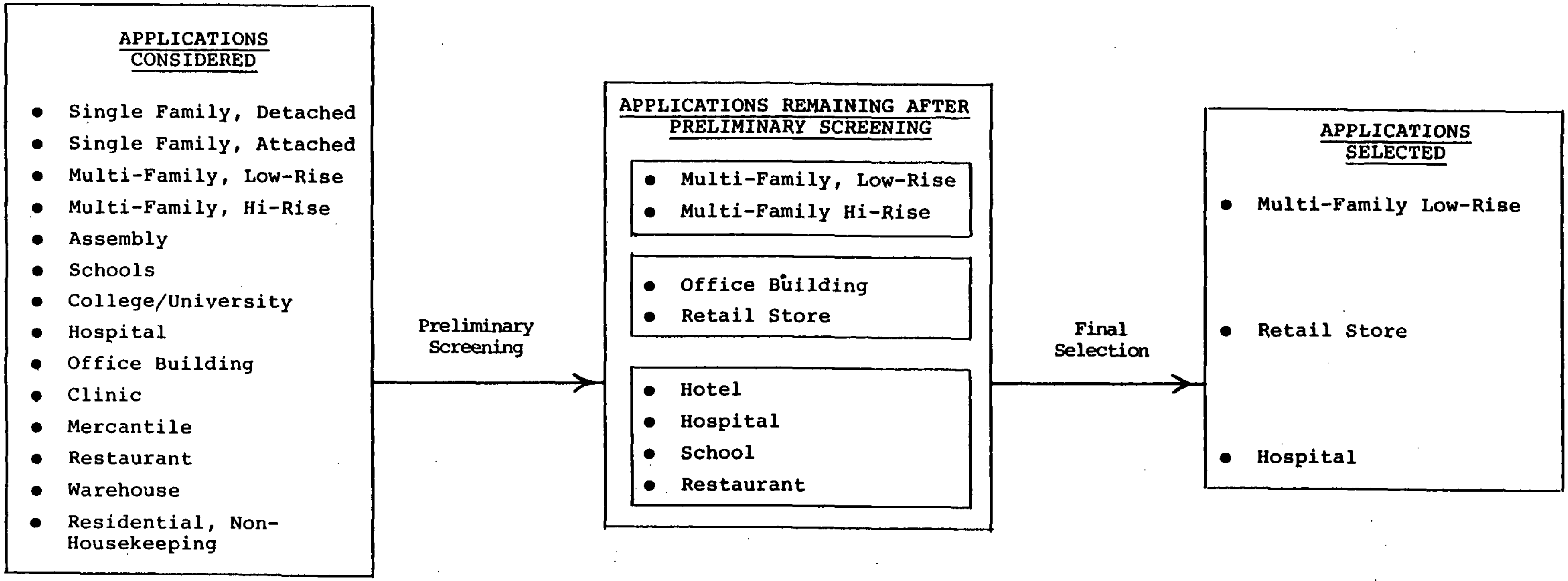


Figure 2-1. Two-Step Selection Process

Step 1: Preliminary Screening

Each of the applications was evaluated in terms of the following screens. Those applications that clearly did not pass one or more of the screens were rejected from further consideration.

- Significance as an R/C Energy Consumer

  The following data were used to test the applications' energy consumption significance. Only new construction was considered.

  i) Annual energy consumption per square foot [1]
  ii) Unit construction costs; ten-year projections of construction volume in dollars by application - Chase Econometrics [2]
  iii) Composite indices for construction costs [3].

  The calculated average construction costs escalation rate was 9.5% per year for 1972 through 1977. This rate was assumed to continue through 1986. Utilizing this data, construction volumes in square meters per year for each building type were used to arrive at energy consumption by building type.

- Electrical Power Requirements for a Typically-Sized Building

  Data from various past studies by MATHTECH and others were consulted to obtain normalized peak electrical power requirements by application. These normalized peak requirements were then applied to corresponding typical building sizes in terms of floor space [1] to obtain typical peak power requirements for each application.

- Thermal/Electric Demand Ratio (TER)

  Annual average thermal-to-electric demand ratios for the various applications were compared with the thermal-to-electric output ratios of the three fuel cell types, using the following data sources:

  i) NASA supplied fuel cell characteristics
  ii) Annual energy requirements for representative residential and commercial buildings [4, 5].

  Calculated average annual thermal/electric demand ratios for R/C applications were compared with the various possible fuel cell TER's, as shown in Figure 2-2.

Six applications were eliminated from further consideration because of their failure to pass one or more of the above screens. Each of these applications with the reason(s) for its elimination is presented in Figure 2-3.

Step 2: Final Selection

In this step three applications were selected from the remaining seven. First, the applications were divided into three groups, with the first group representing residential applications, the second group representing commercial applications with attractive TERs' and high construction rates (hence representing a larger market for the fuel cell), and the third group representing all other applications that passed the first step. One application was then selected from each group, based on the following criteria:

- Load Factors

  Applications with the highest termal and electric load

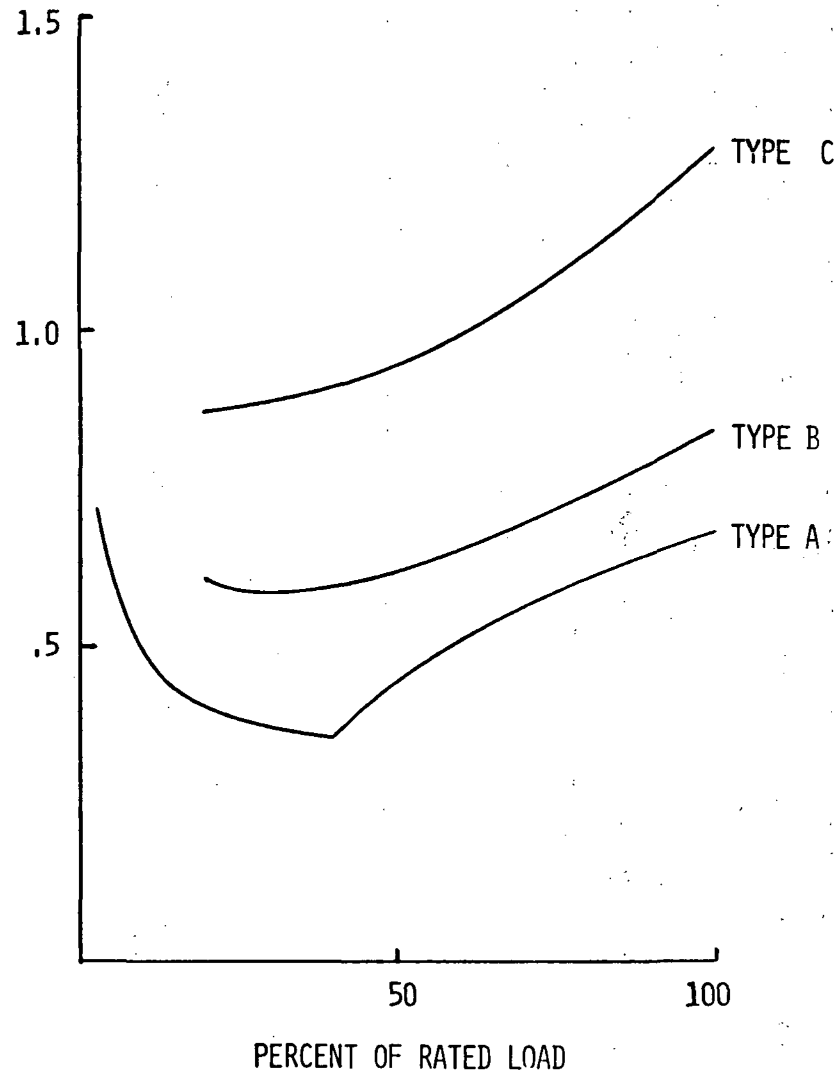


Figure 2-2. Thermal-To-Electric Ratio

Application	Reason for Rejection
Single Family, Detached	Electric Power Requirements Less Than 10kW
Single Family, Attached	Electric Power Requirements Per Dwelling Unit Less Than 10kW
Assembly	Multiple Building Types, Each Representing Small Fraction of R/C Energy Consumption
College/University	Electric Power Requirements Exceed 1MW
Clinic	Represents Insignificant Fraction of R/C Energy Consumption
Warehouse	Summer Thermal Use Too Low

Figure 2-3. Step 1 - Six Applications Rejected

factors received preference.

- Range of Design Requirements

  An effort was made to impose a range of design requirements on the fuel cell system including load profiles, reliability requirements, capacity and others.

In the absence of quantitative technical reasons for discriminating between certain applications, selections were based on the criterion that the final set of applications present a range of design requirements on the fuel cell system, in terms of load profiles, reliability requirements, system capacity, etc.

As a result of this process, the following three applications were selected for energy system design and analysis:

- Multi-family, Low-Rise from the residential group, since it represents a larger fraction of R/C energy consumption than multi-family, high-rise; also, because excellent building design data was available for a low-rise building, and such an application could be selected to present a total electrical power requirement on the low end of the 10 kW to 1 MW range.
- Retail Store from the commercial group, because of load factors that were generally higher than those of office buildings; also, this application represents the middle of the 10 kW to 1 MW power requirements range.
- Hospital from the third group because of hospitals' characteristically high load factors. This application represents the high end of the 10 kW to 1 MW power requirements range.

2.2 Selection of Typical Buildings

Once three applications were selected, the next step was to select typical buildings that represent these applications. Five specific guidelines or criteria were used in selecting these buildings, including the following:

- The buildings should be representative of the application category in terms of:

  i) size
  ii) form (i.e., aspect ratio, number of stories)
  iii) occupancy mix
  iv) exterior envelope
  v) HVAC and lighting systems
  vi) process equipment

- The buildings must comply with ASHRAE Standard 90-75
- Adequate building design information should be available
- The buildings selected should be appropriate in basic design to the three study locations.

Recent actual designs of at least three existing buildings of each generic type were examined, and the most suitable designs with regard to power requirements and typically were selected. Minor modifications were made in the building designs so as to comply with requirements of ASHRAE Standard 90-75, as summarized in Table 2-7.

Table 2-8 lists the three buildings selected, while Tables 2-9 through 2-11 summarize the actual designs. A complete characterization of each building can be found in Appendix B.

2.3 Selection of Geographic Locations

Three geographic locations in the continental United States were selected as potential sites for the evaluation of fuel cell integrated energy systems. The two criteria for selection were:

- the three sites should represent a range of climatic conditions
- the sites should represent a major segment of the United States population.

TABLE 2-7

ASHRAE 90-75 - KEY POINTS

- Design Standard - Not Code
  May be Adopted as Code
  Does Not Override Health and Safety Regulations
- Sets Two Applicable Standards -- Small Residential & Major Bldgs.
- Standards for Component Performance
- Adopted by Consensus -- Good State-of-Art 1974
- Building Envelope Limits Thermal Transmittance
  U-Values and Overall Thermal Transfer Values - Walls, Roof, Floors
  Limits Infiltration
- HVAC: Ventilation Standards
  Equipment Efficiencies, Conversion and Transport
  Control Limits and Sequences
  Designed Maintained Temperatures
- Power: Equipment and Distribution Efficiencies
- Lighting: Illumination Levels -- Power Budget

TABLE 2-8

LIST OF SELECTED BUILDINGS

Selected Applications	Selected Buildings (Size)
Retail Store	Sears, Roebuck and Company Store, Poughkeepsie, N.Y. 1-story, 10,405M^2
Hospital	Good Samaritan Hospital Lebanon, Penna. 4 stories, 11,055M^2
Multi-Family, Low-Rise Apartment Building	Sodders Road Apartments Salem, N.J. 2 stories, 24 DU's 79.3M^2 per DU

TABLE 2-9

DESCRIPTION OF RETAIL STORE

Design Date	1972
Occupancy	Retail/Admin 75%
	Receiving/Stock Rooms 25%
Form	1-Story Rectangular, Flat Roof, No Basement
Construction	Steel Frame, Masonary Walls, Slab on Grade Approximately 6% Glass
ASHRAE 90-75	Walls Exceed, Roof Upgraded, Lighting De-creased
Ventilation*	Retail 897×10^{-6} CMS/M^2 Store 107×10^{-6} CMS/M^2 (ASHRAE 62-73)
Special Features	Small Kitchen, High Lighting Level (32.3W/M^2)
Mods From Original Design	Auto Center Deleted Mall Connections Deleted Mechanical Room Made Interior

* Notation: CMS = M^3/sec

TABLE 2-10

DESCRIPTION OF HOSPITAL

• DESIGN	1971
• OCCUPANCY	PATIENT CARE ROOMS 38% ANCILLARY SPACE 50% MECHANICAL/ELECTRICAL SPACE 12%
• FORM	6 STORY, RECTANGULAR. LEVELS 1 AND 2 ARE LARGER THAN LEVELS ABOVE; CONTAIN EMERGENCY, OPERATING, RADIOLOGY, THERAPY, LABORATORY AND ADMINISTRATIVE FUNCTIONS. LEVELS 3, 4, AND 5 CONTAIN PATIENT CARE ROOMS. LEVEL 6 IS ENTIRELY MECHANICAL/ELECTRICAL. LEVEL 1 IS PARTIALLY BELOW GRADE; ALL OTHERS, ABOVE GRADE. FLAT ROOF.
• CONSTRUCTION	REINFORCED CONCRETE FRAME, FLOORS, AND ROOF SLAB. CAVITY MASONARY WALLS. APPROX. 14% GLASS.
• ASHRAE 90-75	BUILDING ENVELOPE COMPLIES, EXCEPT ROOF UPGRADED
• VENTILATION	AS REQUIRED BY HEW MINIMUM REQUIREMENTS FOR HOSPITAL AND MEDICAL FACILITIES. DHEW PUBLICATION #(HRA) 76-4000. PATIENT CARE 20% OUTSIDE AIR-TREATMENT 100%
• FEATURES	CENTRAL STEAM PLANT HIGH CAPACITY ON-SITE EMERGENCY POWER GENERATORS (DIESEL)
• MODS FROM ORIGINAL DESIGN	WALLS SIMPLIED FROM SITE-UNIQUE TO TYPICAL CONNECTIONS TO OTHER WINGS DELETED

TABLE 2-11

DESCRIPTION OF LOW-RISE APARTMENT BUILDING

Occupancy	24 Dwelling Units, Each 2-Bedroom
Form	2-Story Rectangular, Sloped Roof, No Basement
Construction	Wood Frame, Brick Veneer Walls
ASHRAE 90-75	Complies, Except Roof Upgraded (Chicago Only)
Ventilation	$0.04 M^3/sec$ (Kitchen and Bath Exhaust Only) (ASHRAE 62-73)
Features	Laundry in Each Dwelling Unit, Outside Entrance Each Dwelling Unit
Mods From Original Design	Change From 12 to 24 DU per Building

Because of these criteria, the following sites were selected:

- Washington, D.C.
- Chicago, Illinois
- Dallas, Texas

These locations were selected to represent climates that would result in

i) a significant winter heating load and a significant summer cooling load

ii) a high winter heating load and a relatively low summer colling load

iii) a low winter heating load and a high summer cooling load.

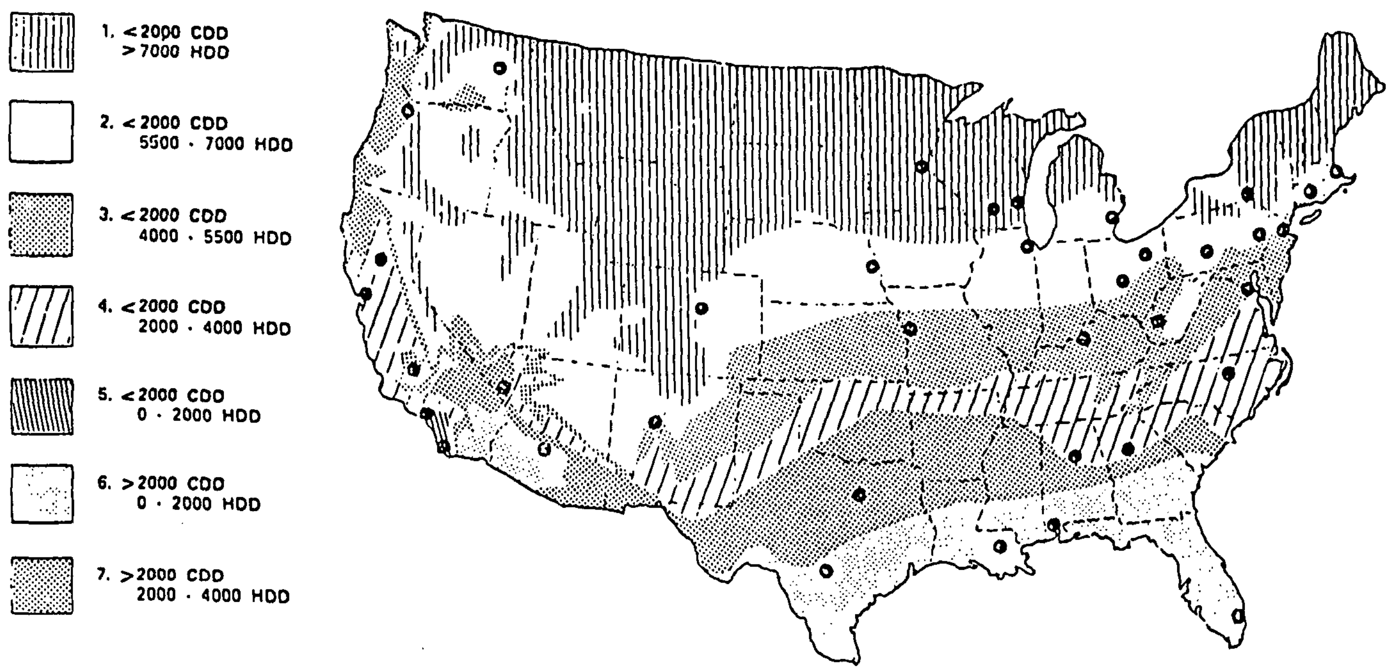
A location that featured both low heating and cooling loads was judged to be an unattractive site for an integrated energy system.

Space heating and cooling loads for the various regions of the continental United States were based on a classification by heating and cooling degree days, as illustrated by Figure 2-4. Of the six major degree day regions from north to south, Chicago, Washington and Dallas were selected as major population centers that represent the "top two", the "middle two", and the "bottom two" regions, respectively. As the climatic data presented in Table 2-12 indicates, the selected cities represent fairly well the three climates described above.

2.4 Building End-Use Energy Loads Estimates

2.4.1 Selection of AXCESS as the Loads Analysis Program

This study required the calculation of building energy use over time, rather than merely peak demands, as typically required for system design. Specifically, it was necessary to break energy use into end-use components assignable to thermal and electrical energy



Source: Phase One/Base Data for the Development of Energy Performance Standards for New Buildings: Task Report, Climatic Classification, AIA Research Corporation, January, 1978.

Figure 2-4. Heating and Cooling Degree Day Regions

TABLE 2-12

CLIMATIC DATA FOR SELECTED LOCATIONS

Location	Washington, D.C. (1957)	Chicago, IL (1974)	Dallas, TX (1975)
Heating Degree* Days	2468 (1957-1958 Season)	3309 (1973-1974 Season)	1301 (1974-1975 Season)
Cooling Degree* Days	798	428	1449
Average Temperatures, °C			
Annual	14	10	19
Coldest Month	1	-4	8
Hottest Month	26	24	29

* Units used in expressing degree days are "degrees Celsius x days."

and to develop daily, weekly, monthly and annual profiles, in order to permit system analysis and design in terms of thermal/electrical energy balance and storage and to permit detailed reliability analysis. In order to meet these requirements, a number of computerized building loads analysis programs were reviewed, and one was selected and used by Ballinger to estimate loads for the selected buildings.

The following criteria were used in selecting an analysis program:

- a computerized method in order to meet time, cost and iteration requirements.
- availability within the project time frame
- an established history of acceptable operation
- ability to analyze multizone buildings
- ability to calculate building loads, in different geographical locations, for all conventional construction types and building systems
- ability to use hourly weather information for an entire year
- ability to measure, individually, all load components of a building
- acceptable accuracy relative to other analysis techniques
- cost effectiveness in terms of project budget
- acceptable ease of use; familiarity by available personnel, or short familiarization period
- ability to accept input data at a level of detail consistent with project needs.

The search evaluation focused on three basic areas:

- programs previously used by Ballinger
- programs evaluated by NBS for applicability to the MIUS program
- program analysis and evaluation by AIA/Research Corporation for use in the Building Energy Performance Standards (BEPS) Program, for DHUD and DOE.

It was found that available analysis programs differ in many important respects. For example, a program intended to compare building envelope performance must accept very detailed descriptions of wall and roof materials and may approximate other features, while a program intended to compare HVAC systems may similarly minimize details of other (constant) building elements. Either may use rather simple weather data and may exclude loads other than space conditioning. Programs directed toward a realistic assessment of actual energy use, and particularly those considering thermal/ electrical balance, must include all energy uses.

A total of 16 programs were identified and reviewed for use in this study. Of these, eight were selected and examined in detail. Based on the comparative evaluation of loads programs, the AXCESS program, owned by the Edison Electric Institute, was selected for use in this study. AXCESS met all the criteria for selection, particularly in the areas of ease of use and availability. The program was locally available from an experienced source which could provide the turnaround time and consultation which were needed. AXCESS has an established operational history for acceptable accuracy, based on its use in the Building Energy Performance Standards (BEPS) Program sponsored by DOE and HUD, and it correlates favorably with other programs.

2.4.2 Use of the AXCESS Program to Estimate Building End-Use Loads

The AXCESS Program was used to estimate end-use energy loads for each of the three selected buildings in each geographic location. Three building energy systems were simulated, including an all-electric, gas-electric, and a district "system." The district system, which assumed a hydronic thermal distribution system, provided the required estimates of the end-use loads that would be experienced by a centralized OS/IES.

Table 2-13 lists the types of inputs required for the AXCESS Program. Although a complete description of all inputs for each building and location is beyond the scope of this report, some of the more important input assumptions and data are summarized in Appendix C.

Table 2-14 summarizes the general output information produced by AXCESS. The results for the conventional systems will be described in Chapter 3. Figures 2-5 through 2-6 illustrate the end-use load profiles obtained from AXCESS output for the selected retail store building for typical seasonal days and summer and winter design days in Washington, D.C. A complete set of load profiles for the other selected buildings and locations may be found in Appendix D. Annual energy consumption by end-use is summarized in Figure 2-7 for all three of the selected buildings.

References

1. AIA Research Corporation, Phase One/Base Data for the Development of Energy Performance Standards for New Buildings; Final Report, January, 1978.
2. AIA Research Corporation, Phase One/Base Data for the Development of Energy Performance Standards for New Buildings: Task Report, Building Classification, January, 1978.
3. U. S. Department of Commerce, Bureau of Census, Statistical Abstract of the United States, 1978.
4. FEA/A.D. Little, Energy Conservation in New Building Design: An Impact Assessment of ASHRAE Standard 90-75, Conservation Paper No. 43B, 1976.
5. Decision Sciences Corporation, Economic Evaluation of Total Energy, Technical Report 1973.

TABLE 2-13

AXCESS INPUT

FOR ALL LOCATIONS/SYSTEMS	
BUILDING DESCRIPTION	Areas, U Values, Mass Factors, Glass Areas, Shading Coefficients, Orientation, Zones
OPERATING PROFILES	Occupancy, Lighting, DHW, Heating, Cooling, Process Power
DESIGN CONDITIONS	Temperature, Humidity, Occupied and Unoccupied Periods
LIGHTING	Interior and Exterior Watts/M^2
PROCESS EQUIPMENT	Demand Level, Energy Source
OCCUPANCY	Number Persons, Sensible and Latent Heat
FOR EACH OF THREE SYSTEMS (ALL-ELECTRIC, GAS-ELECTRIC, DISTRICT)	
HEATING AND COOLING PLANTS	Type, Capacity, Energy Source, Efficiency Curves
DISTRIBUTION SYSTEMS	Type, Capacity, Fan/Pump Sizes, Efficiency Curves, Reset Points, Economizer Cycles, Outside Air Percent
FOR EACH OF THREE LOCATIONS	
HOURLY WEATHER DATA	NOAA Try (Test Reference Year)

TABLE 2-14

AXCESS OUTPUT

FOR EACH BUILDING/LOCATION/SYSTEM:

For Each Selected End-Use

- Energy Used Each Hour of Every Fifth Day
- Monthly Total Energy Use
- Annual Total Energy Use
- Peak Demand by Month, Day, Hour

End Uses Selected For This Analysis

SYSTEM A ALL-ELECTRIC	SYSTEM B GAS-ELECTRIC	SYSTEM C DISTRICT
Cooling	Cooling	Cooling
Heating	Heating	Heating
Domestic Hot Water	Commercial Hot Water	Commercial Hot Water
Cooking	Cooking	Cooking
Other Electric	Other Electric	Other Electric
Process Use*	Process Use*	Process Use*

* Hospital Application Only.

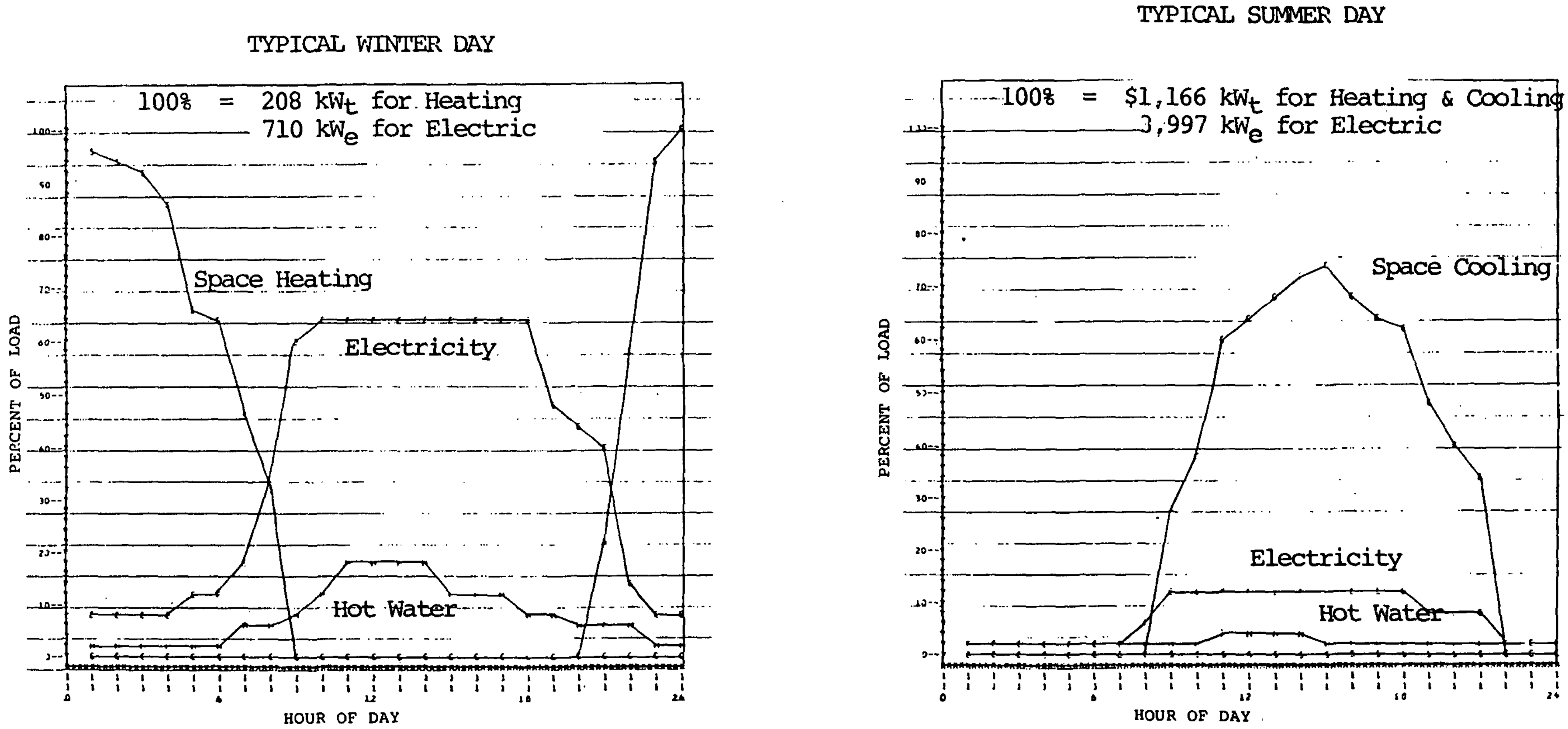


Figure 2-5. Hourly End Use Load Profiles for a Retail Store, Washington, D.C.: Typical Seasonal Days

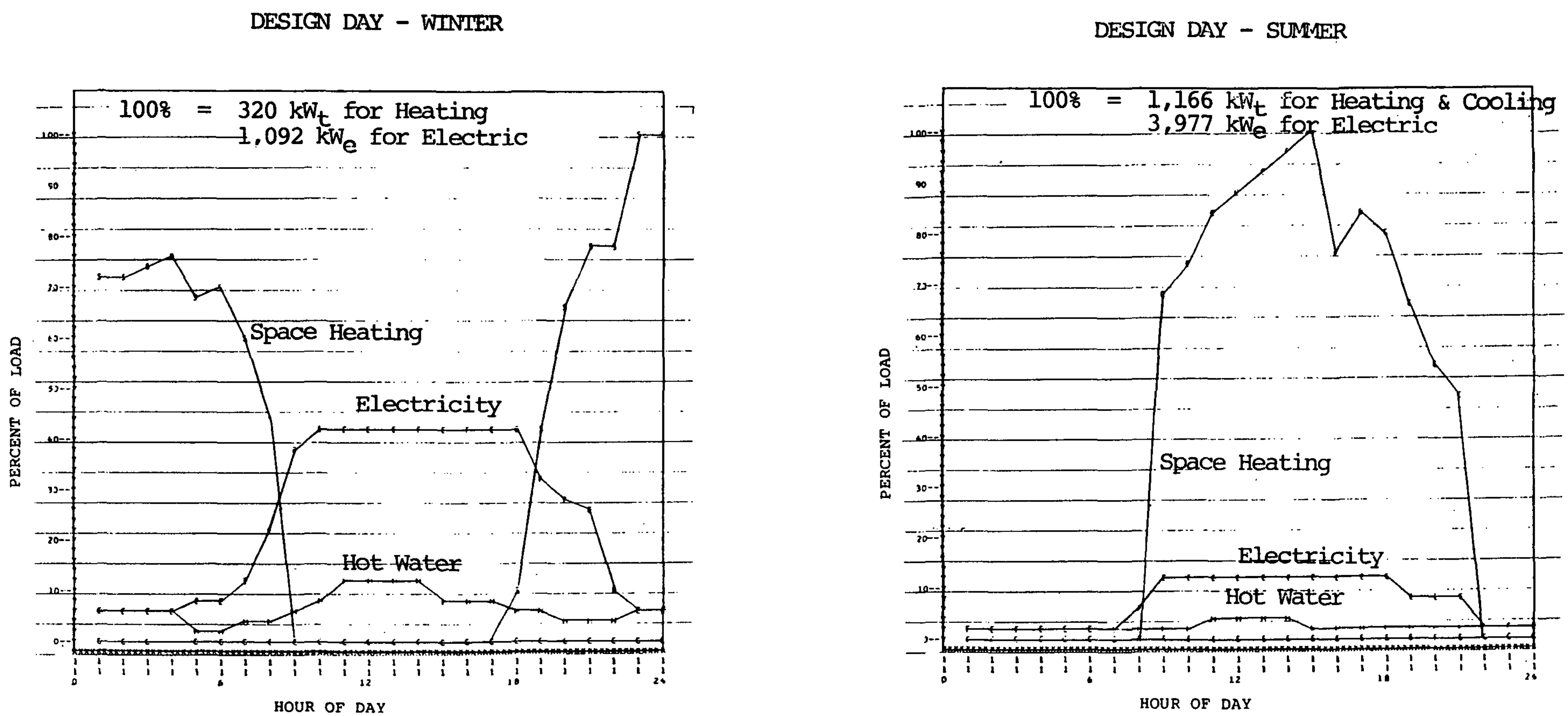
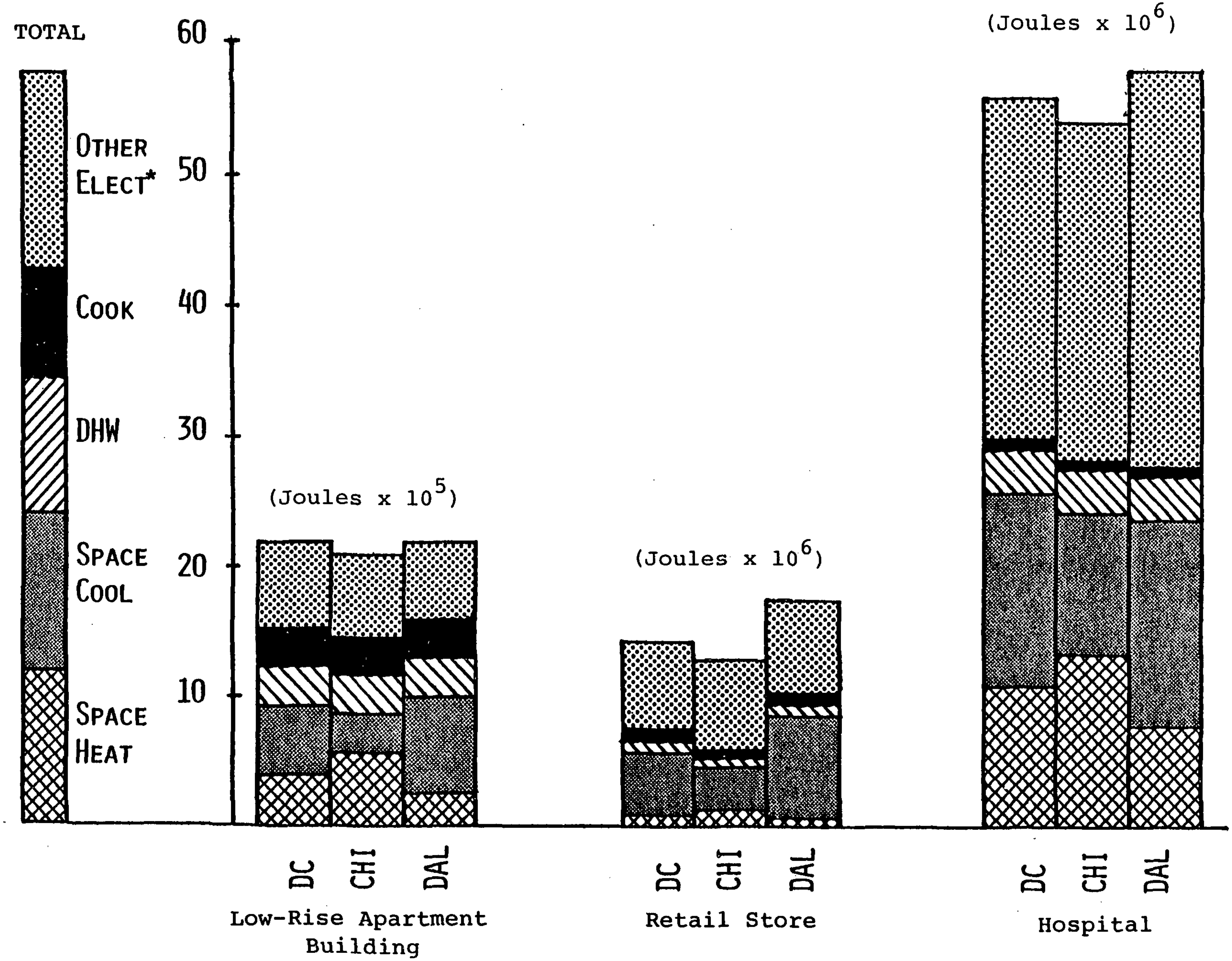


Figure 2-6. Hourly End Use Load Profiles for a Retail Store, Washington, D.C.: Design Seasonal Days



* Includes all end-uses that can be met only with electricity.

Figure 2-7. AXCESS Analysis of Annual Building End-Use Energy Demands

CHAPTER 3

DESIGN OF CONVENTIONAL ENERGY SYSTEMS

3.1 General Approach

For each application and each location, two conventional energy systems were designed. One system used electrical energy to serve all building loads, the other used natural gas and electricity, as appropriate to the nature of the loads.

The conventional energy system designs were required to be technically and economically representative of sound current practice, and to serve three purposes specific to this study.

- Identify costs and energy consumption for subsequent comparison with fuel cell systems
- Provide a basis for defining the interface between fuel cells and conventional HVAC equipment.
- Identify any loads associated with energy distribution

All design was performed by engineers normally engaged in the design of HVAC and electrical systems for commercial scale buildings. Standard procedures were used in selecting and sizing systems and components, and in developing system schematics. Designs were developed only to the level of detail necessary to fulfill the requirements of this study.

3.2 Design Guidelines

Many forces acted on design decisions. However, all designs were developed using the following guidelines:

- The design concepts were those which would reasonably be selected for each application and location under study. Exceptions to this were the All-Electric Hospital and, to a lesser extent, the All-Electric Retail Store. Lacking gas, oil would normally be used, rather than electricity, in these two cases.

- The energy systems actually installed in the original buildings on which the study buildings are based, were used, to the extent that they conformed with 1978-79 design practice.

- Performance characteristics were selected to comply with the requirements of ASHRAE Standard 90-75.

- Control zones were simplified to the maximum degree possible without significantly affecting energy use, because of the cost and time limitations of the contract.

- The gas-electric designs utilized natural gas to serve all loads for which gas would typically be used in actual practice. These included, for all applications, space heating, domestic water heating, and cooking.

Initially, all equipment was sized, and air volumes determined, using standard ASHRAE procedures, including the requirements of ASHRAE 90-75. Equipment sizes were then adjusted for final specification and cost as indicated by the output of the AXCESS Energy Analysis.

3.3 Design Procedures and Resulting Designs

The specific conventional system design procedures used for each of the three prototype buildings are described below and the resulting designs are summarized.

3.3.1 Multi-family Residential

The selection of systems was based on discussions with representatives of the National Association of Home Builders (NAHB), and with developer/builders of small scale residential buildings in Philadelphia, Chicago, and Dallas.

The discussions consistently indicated that the dominant forces influencing system/equipment selection were low initial cost and ready acceptability by potential tenants. The ability to meter energy use by dwelling unit is increasingly important, and maintenance should require moderate and widely available skills.

The thermal distribution options are summarized in Table 3-1. For small scale multi-family residences, air is the preferred final distribution medium, with small unitary heating/cooling equipment. Central plants may be used in larger scale apartments (100 or more dwelling units).

The designs are shown schematically on the following drawings:

Residential, All-Electric, HVAC	Figure 3-1
Residential, All-Electric, Electrical	Figure 3-2
Residential, Gas-Electric, HVAC	Figure 3-3
Residential, Gas-Electric, Electrical	Figure 3-4

Major equipment is specified in Appendix E.

Because of the building size and configuration, only four exterior exposure zones were defined for control and energy analysis.

3.3.2 Retail Store

The selection of systems was based on Ballinger's experience in the design of the study building and other Sears retail stores.

TABLE 3-1

THERMAL DISTRIBUTION OPTIONS CONSIDERED FOR LOW-RISE APARTMENT BUILDING

	TEMPERATURE CONTROL	FIRST COST	MAINTENANCE COST	ENERGY COST
● Central Plant - Hot and/or Chilled Water to Each Dwelling Unit (DU) - Fan Coil w/Ducted Air Each DU	Good	High	Low	Low
● Unitary* - DX Cooling, or Heat Pump, with Ducted Air, Each DU - Heating, Each DU, by Heat Pump, Electric Resistance, or Gas/Oil Air Furnace	Varies	Low	High	Varies
● Combination - Central Plant Heating, Hydronic Distribution to Radiation, Convection, or Fan Coil Units - DX Cooling with Ducted Air, Each DU	Good	Moderate	Moderate	Moderate

* Option Selected.

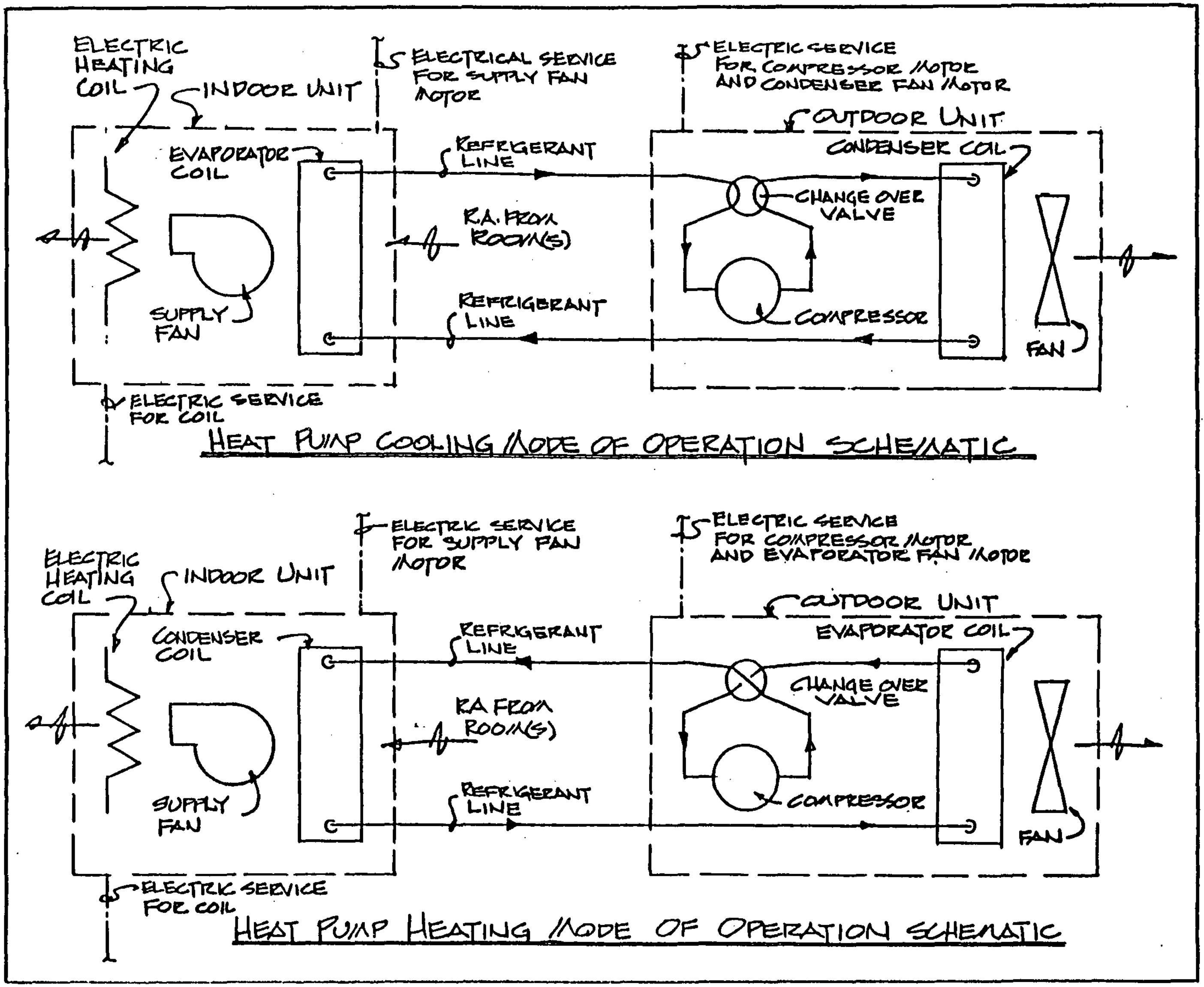


Figure 3-1. HVAC System Schematic All-Electric: Low-Rise Apartment Building

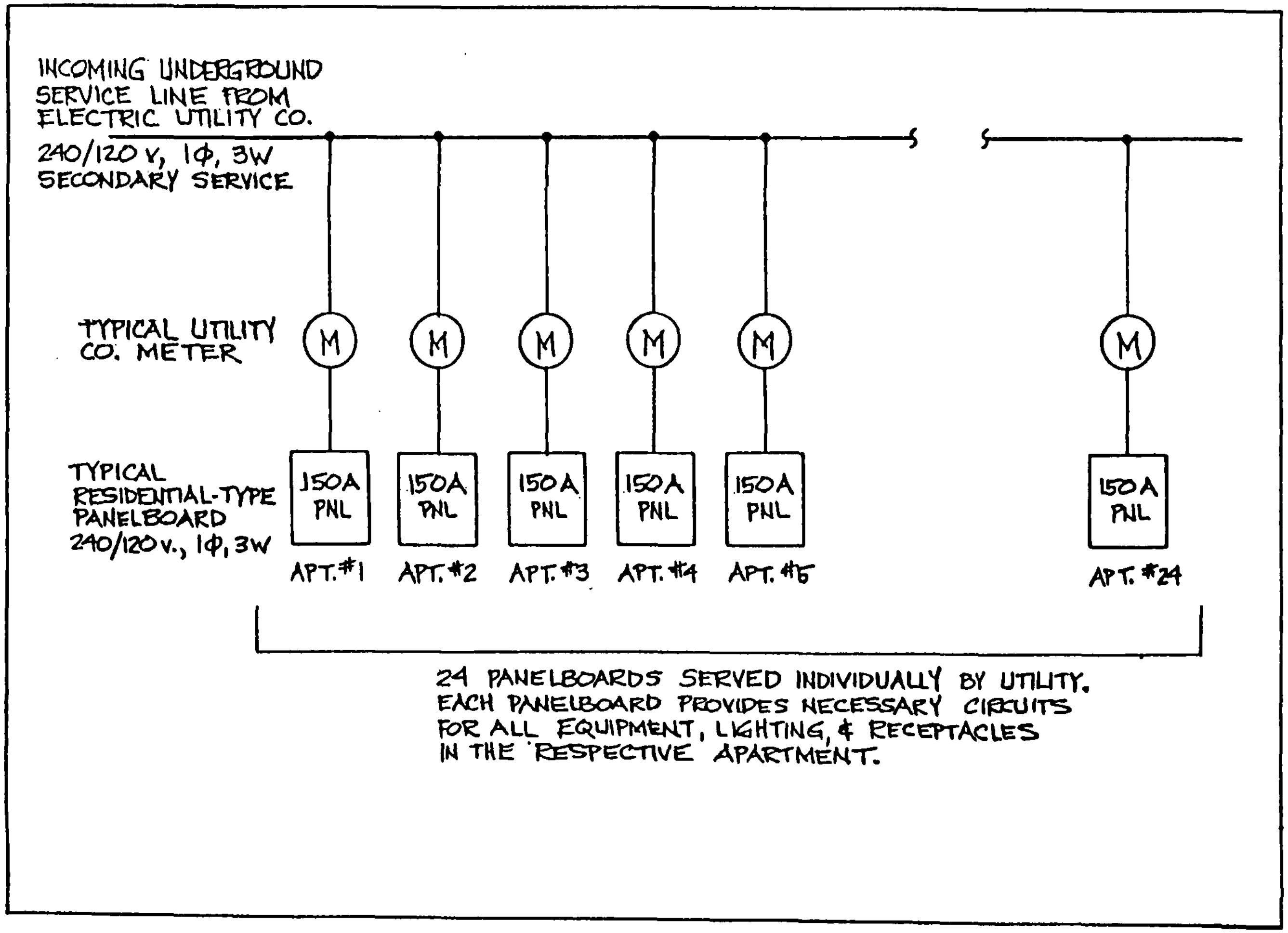


Figure 3-2. Electric Schematic For All-Electric System: Low-Rise Apartment Building

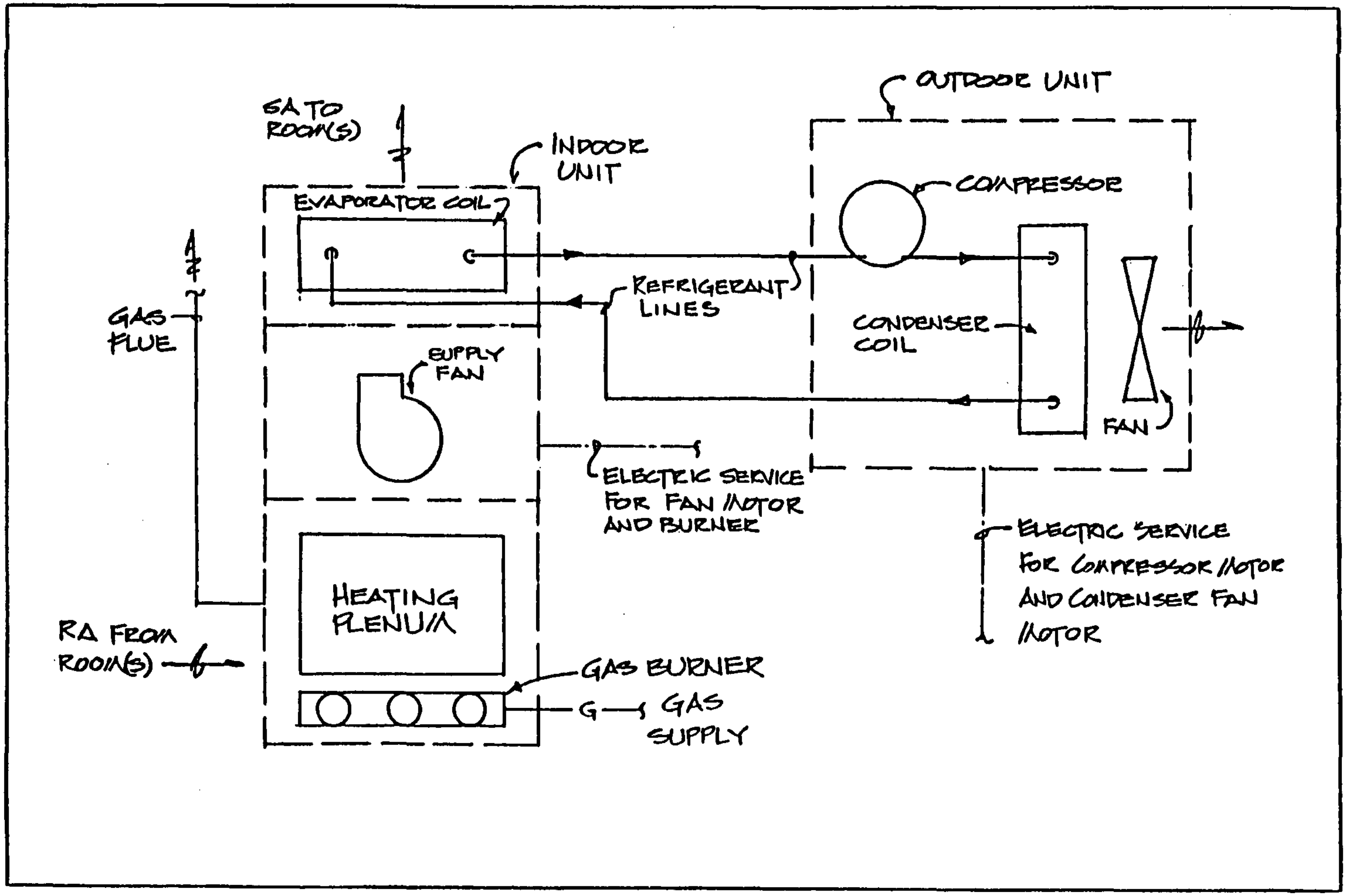


Figure 3-3. HVAC Schematic For Gas/Electric System: Low-Rise Apartment Building

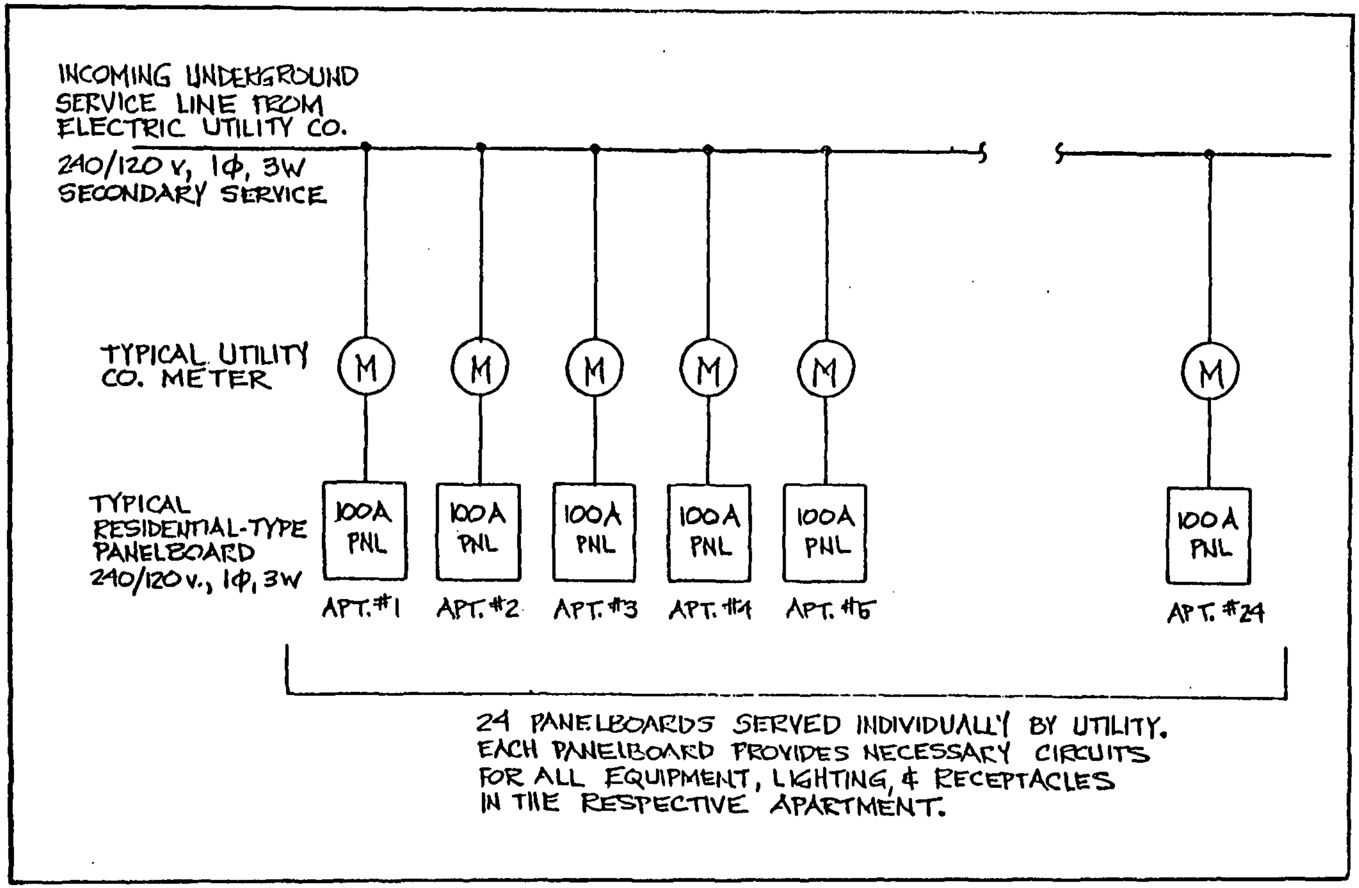


Figure 3-4. Electrical Schematic For Gas/Electric System: Low-Rise Apartment Building

Current owner preference was confirmed by discussion with Sears facilities personnel responsible for the three locations studied. Design philosophies reflect the building scale and the values of a major retailer.

Equipment reliability, and the ability of the systems to maintain stable conditions, are the determining forces. Equipment must be easily maintainable, but a capable maintenance staff is available. Both initial and operating costs are considered important, but performance needs justify some cost premiums.

Thermal distribution options are shown in Table 3-2 and Figure 3-5. The gas-electric central plant design is the preferred system for the quality level represented by Sears Roebuck; gas-electric unitary systems are also commonly found in retail stores. The all electric system is atypical in that oil-electric is a more usual alternative in the absence of gas.

The designs are shown schematically on the following drawings:

Retail Store, All-Electric, HVAC	Figure 3-6
Retail Store, All-Electric, Electrical	Figure 3-7
Retail Store, Gas-Electric, HVAC	Figure 3-8
Retail Store, Gas-Electric, Electrical	Figure 3-9

Major equipment is specified in Appendix E.

The building was divided into an interior zone and four exterior exposure zones.

3.3.3 Hospital

The dominant forces influencing design are the need for reliability and the wide range of activities and schedules which must be accommodated. Some process steam is typically

TABLE 3-2

THERMAL DISTRIBUTION OPTIONS FOR RETAIL STORE

Type	Temperature Control	First Cost	Maintenance Cost	Energy Cost
Principal System (Space Loads)				
- Central Plant Ducted Air	Good	High	Low	Low
- Central Plant, Hydronic Distribution to Local Air Handling Units*	Good	Medium	Medium	Low
- Multiple Local Units Thermal Conversion Plus Air Handling	Fair	Low	High	Varies
Supplementary System (Perimeter Loads)				
- Hydronic Radiation/Convection Units*	Good	High	Low	Low
- Electric Resistance	Good	Low	Low	Varies

* Option selected for this study.

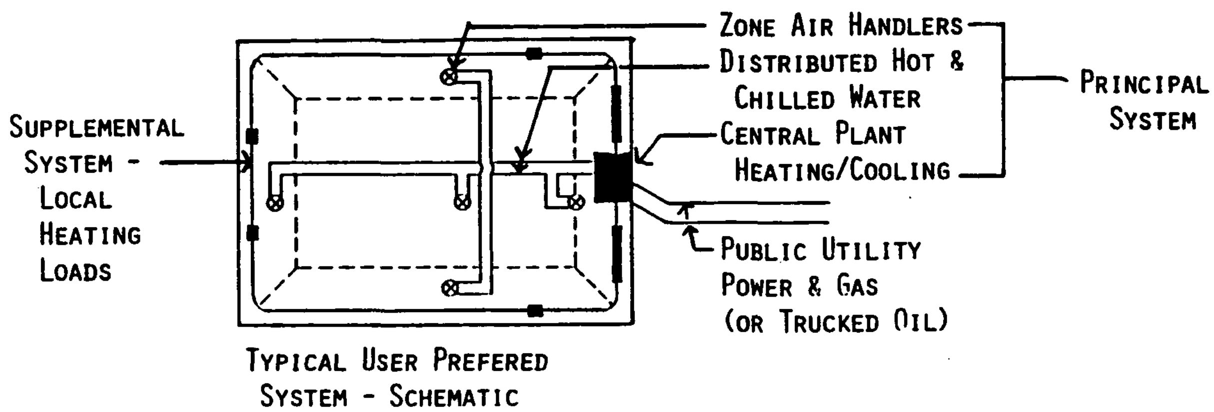


Figure 3-5. Thermal Distribution System Options: Retail Store

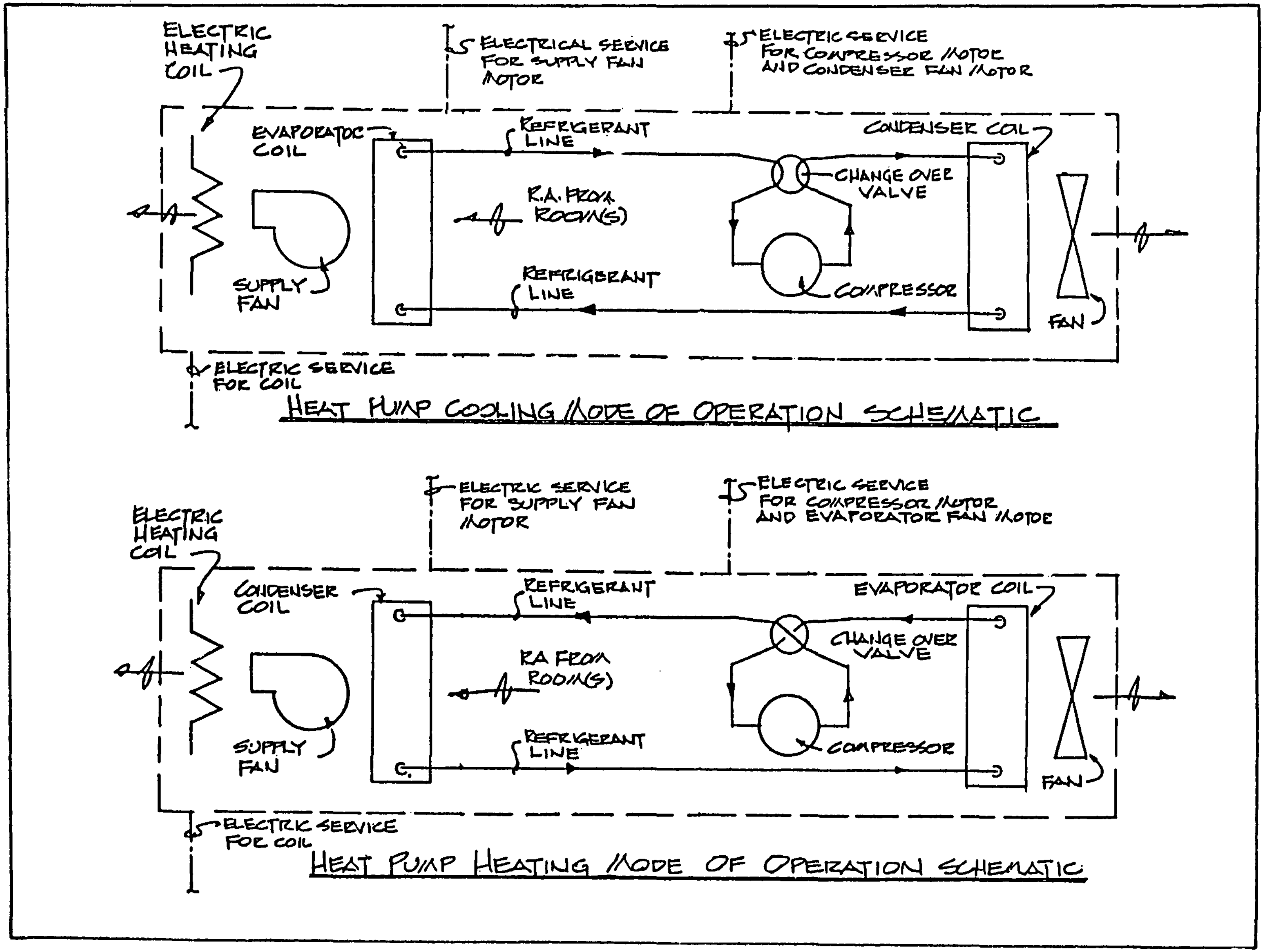


Figure 3-6. HVAC Schematic For All-Electric System: Retail Store

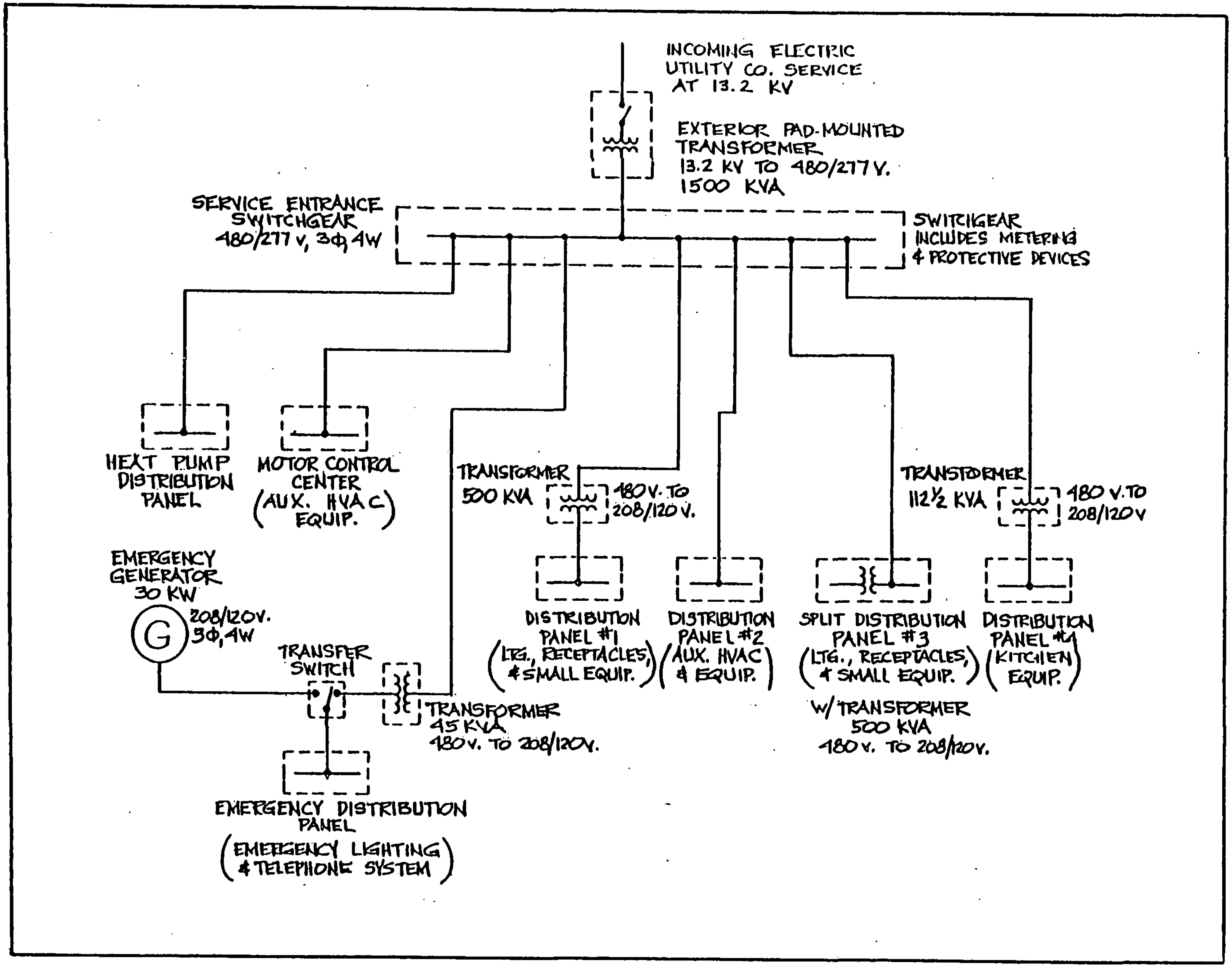


Figure 3-7. Electrical Schematic for All-Electric System: Retail Store,

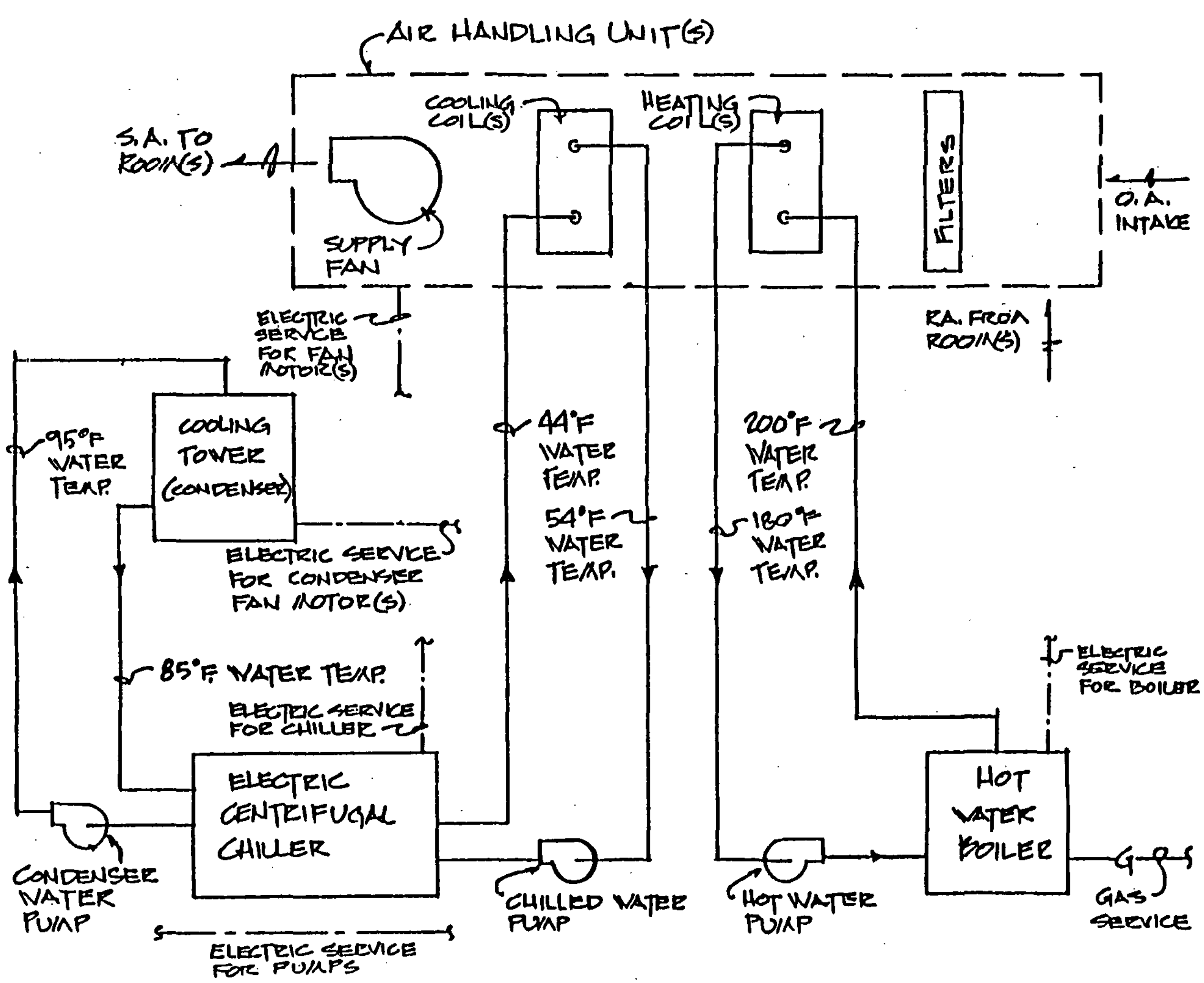


Figure 3-8. HVAC Schematic For Gas/Electric System: Retail Store

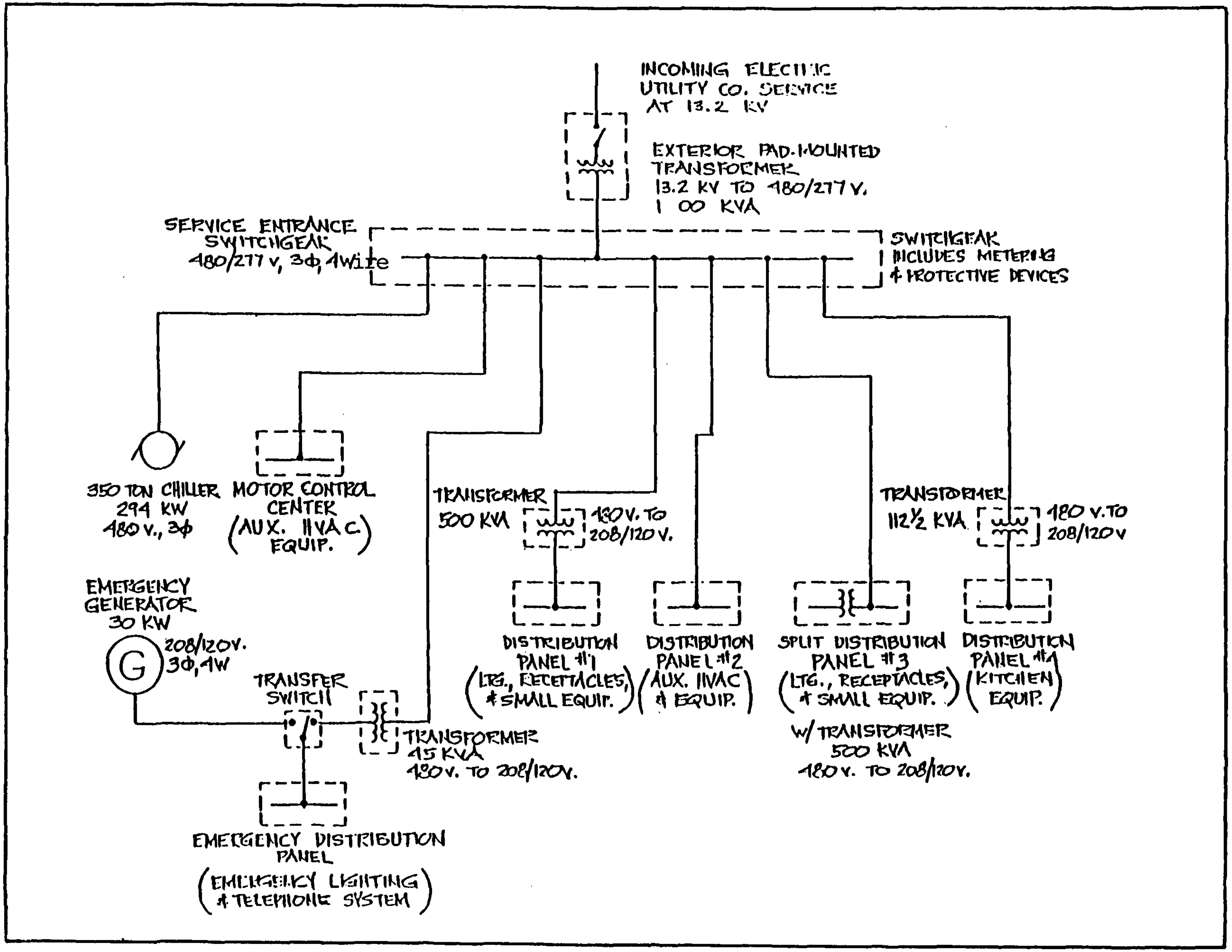


Figure 3-9. Electrical Schematic for Gas/Electric System: Retail Store,

required. A capable on-site maintenance staff is normally available. Initial and operating costs are less significant than performance.

Thermal distribution options are shown in Table 3-3.

The gas-electric system is essentially identical to that used in Ballinger's design for the actual building on which the study building is based. However, system selection and design were also influences by Ballinger's more recent experience with comparable hospitals. An all-electric design generally is not used for a hospital of this type and size, but was included in this study for completeness.

Absorption refrigeration is typically used in hospitals, with or without vapor compression refrigeration, primarily for independence from electric power failure.

The designs are shown schematically on the following drawings:

Hospital, All-Electric, HVAC	Figure 3-10
Hospital, All-Electric, Electrical	Figure 3-11
Hospital, Gas-Electric, HVAC	Figure 3-12
Hospital, Gas-Electric, Electrical	Figure 3-13

Major equipment is specified in Appendix E.

For this application, major use zones as well as exposure zones, were defined, to reflect the effect of different use profiles and design conditions.

TABLE 3-3

THERMAL DISTRIBUTION SYSTEM OPTIONS FOR HOSPITAL

Space/System	Temperature Control	First Cost	Maintenance Cost	Energy Cost
Ancillary (Treatment Space)				
- Conditioned Air*, Tempered by Central Plant Cooling and Heating	Good	High	Low	Low
- No Other Valid Alternative				
Patient Care Spaces				
- Induction -- High Pressure Distribution of Conditioned Air Tempered at Central Plant	Good	Very High	Low	Low
- Fan Coil Units,* Tempered by Hot/Chilled Water From Central Plant	Good	Moderate	Low	Moderate

* Option Selected

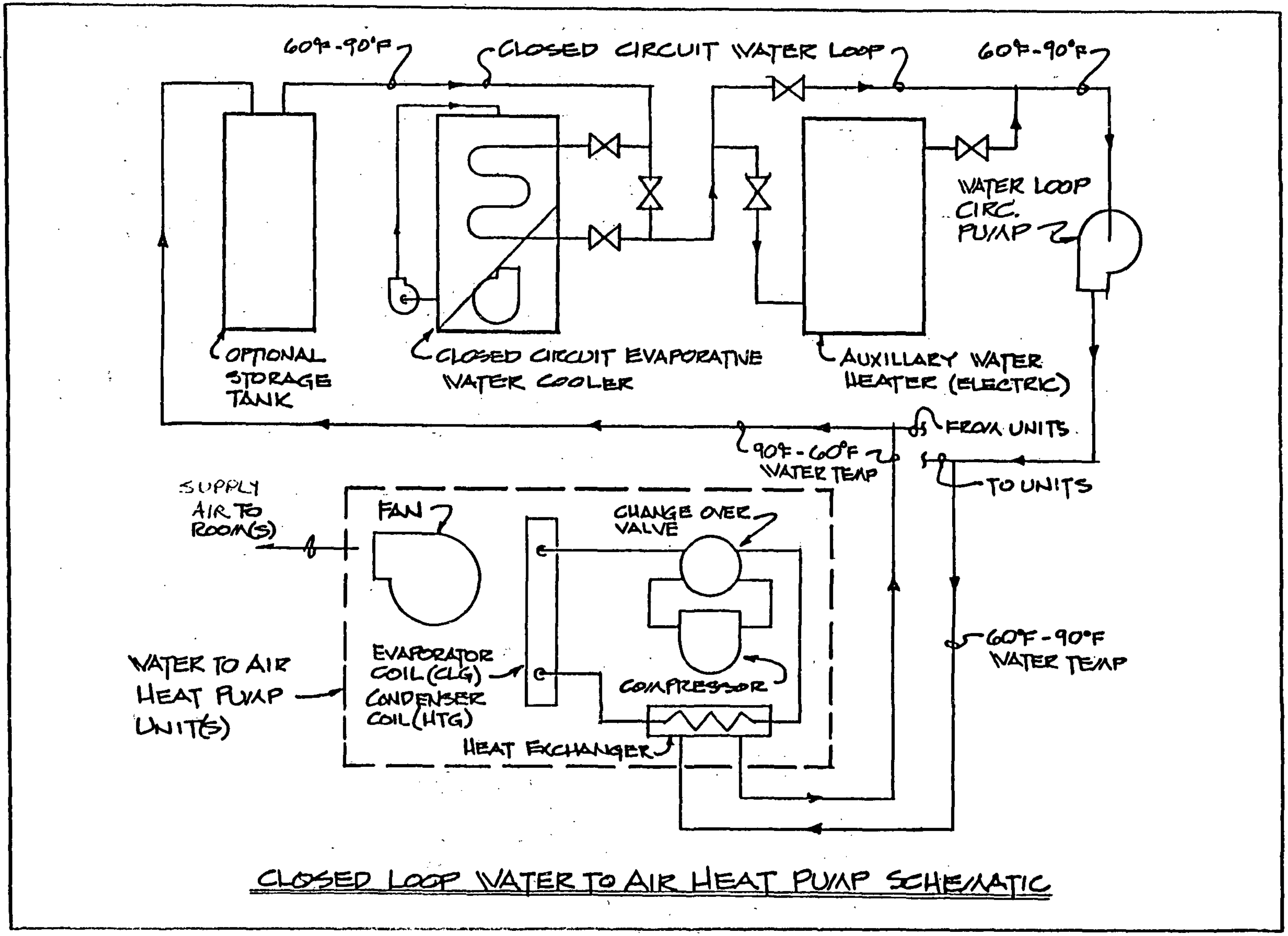


Figure 3-10. HVAC Schematic for All-Electric System: Hospital

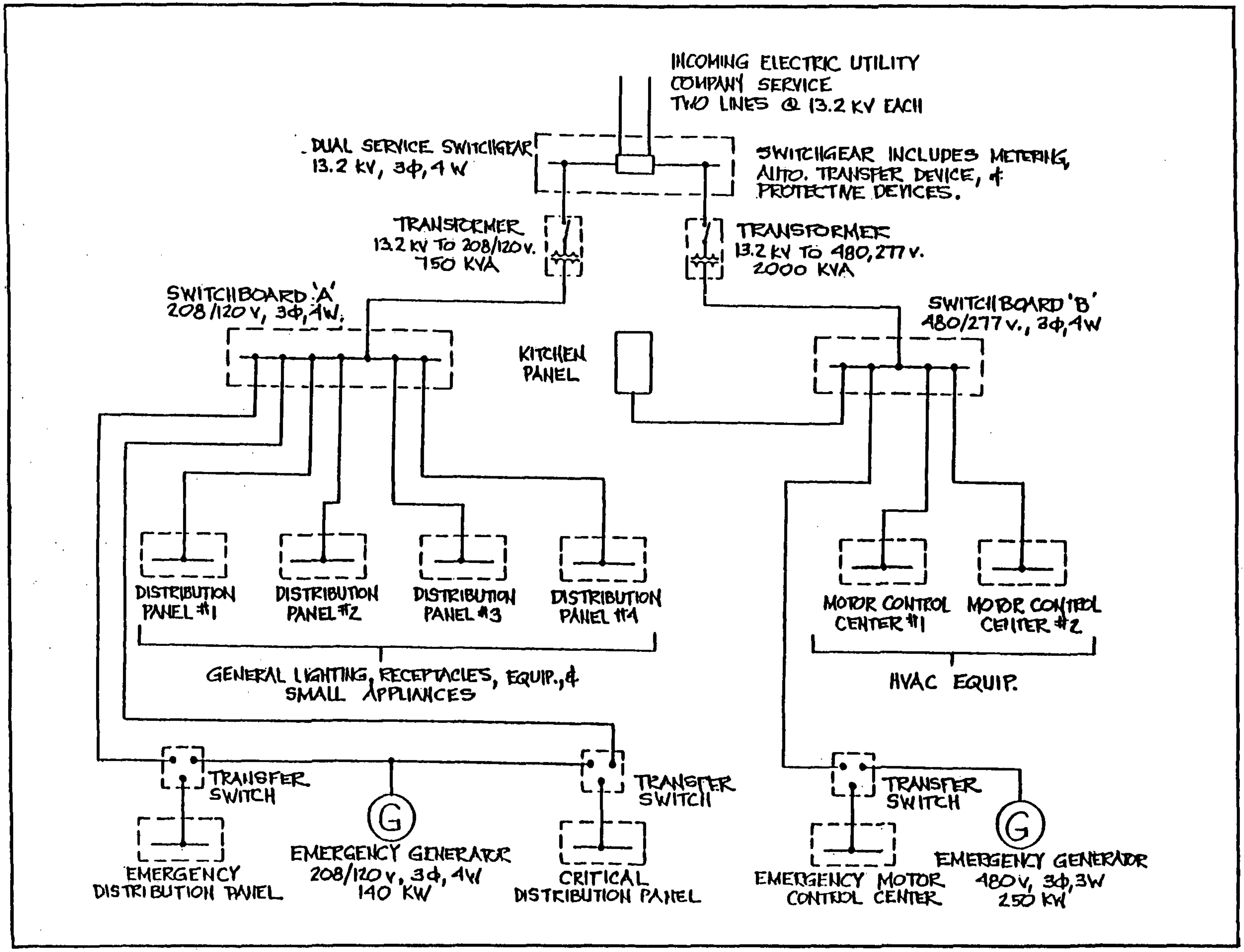


Figure 3-11. Electrical Schematic for All-Electric System: Hospital

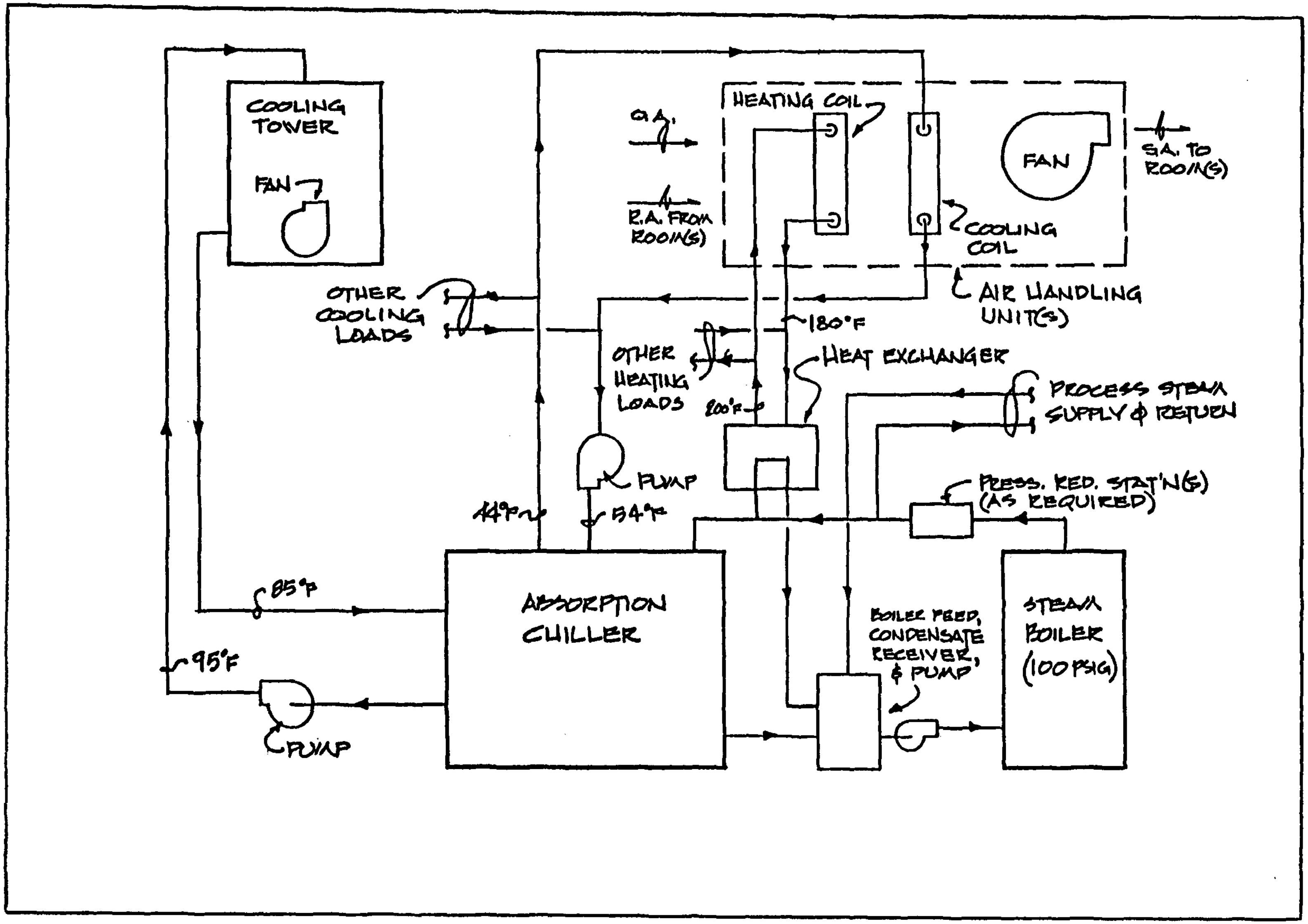


Figure 3-12. HVAC Schematic for Gas/Electric System: Hospital

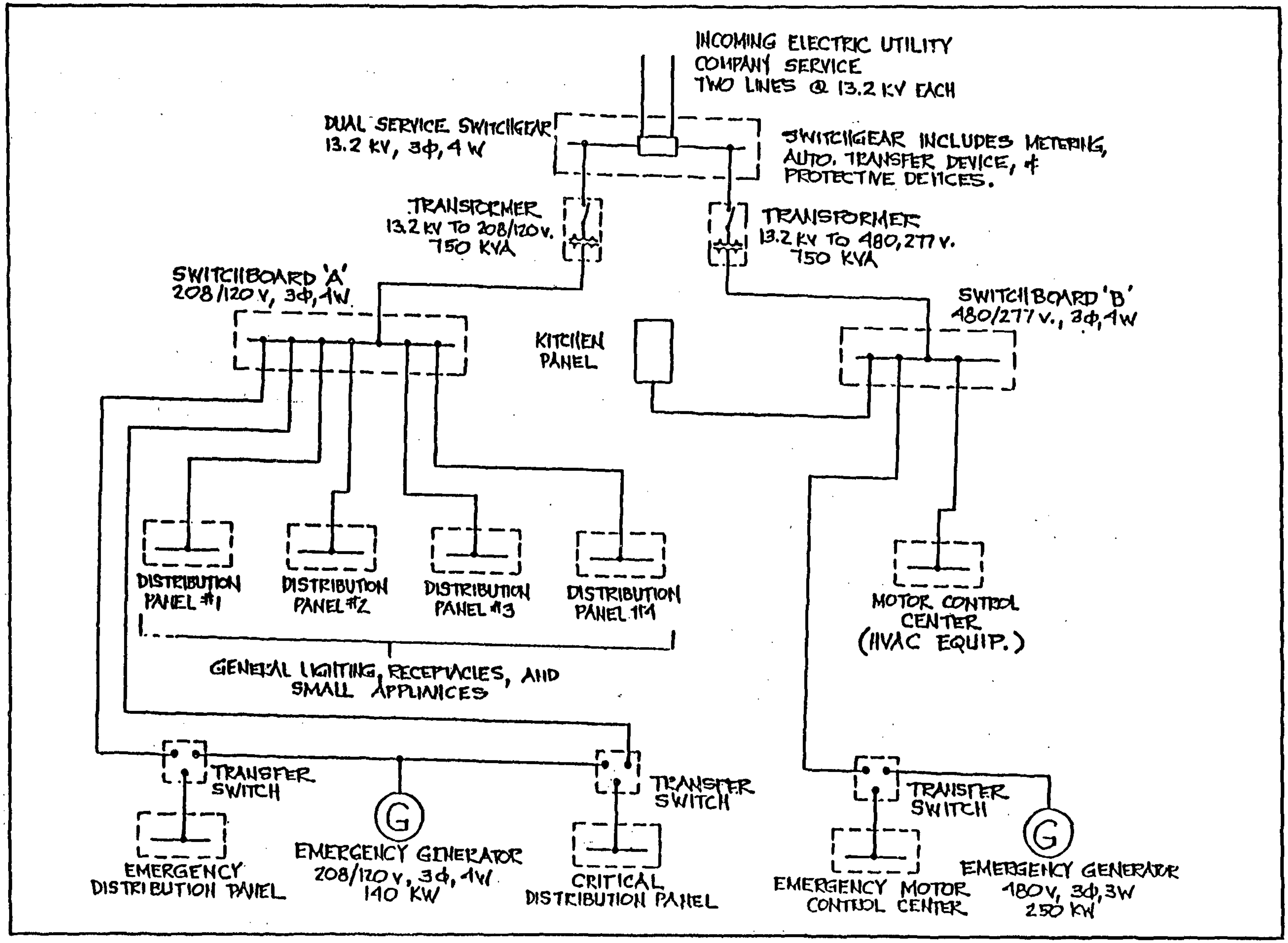


Figure 3-13. Electrical Schematic for Gas/Electric System: Hospital

CHAPTER 4

DESIGN AND SIMULATION OF FUEL CELL SYSTEMS WITHOUT UTILITY TIE-IN

Fuel cell, on-site integrated energy systems were designed for each building in each location, first under the assumption that there was no interconnection with a local electric utility and then under the assumption that such an interconnection did exist. This chapter describes the design and simulation of fuel cell systems under the former assumption. Sections 4.1 and 4.2 present the integrated energy system design criteria and fuel cell characteristics, respectively, as prescribed by NASA. Then, the approach used for design, simulation and reliability analysis is described in Section 4.3. Finally, Section 4.4 presents the fuel cell OS/IES designs that result from the above design and simulation process.

4.1 Design Criteria

The following criteria guided the design of the on-site fuel cell systems:

- All electricity was generated on-site by a phosphoric acid fuel cell power plant.
- The usable heat produced by the fuel cell system was utilized to the maximum extent possible, consistent with the goal of minimal life cycle cost.
- Fuel for the fuel cell powerplant was gas, and no on-site fuel storage was required.
- The combination of equipment to provide the end-use energy demands was chosen so that the thermal and electrical energy needs match the available energy from the fuel cell

power systems as closely as possible in order to minimize the need for supplemental furnaces or boilers.

- Thermal energy storage was considered as a means of matching the demand for thermal energy with the thermal energy available from the fuel cell.

- The fuel cell systems were designed to provide electric service with a reliability equal to the reliability provided by typical electric utilities.

4.2 Fuel Cell Characteristics

Operating characteristics of the three types of fuel cells also were provided by NASA. All three fuel cells are of the phosphoric acid type and may be briefly characterized as follows:

Type A - Present Generation Fuel Cell
Type B - Advanced Technology Fuel Cell
Type C - Near-Term Technology Fuel Cell

The Type A and Type C fuel cell power plants are representative of those being developed for commercialization in the 1985 time frame, while the Type B fuel cell power plant represents a significant technology advance over the other two types.

For the fuel cell system design and analysis data were required on the gas input and electrical and thermal outputs of each fuel cell considered. Figure 4-1 illustrates the fuel cells' total efficiencies.

Fuel cell part-load characteristics have a significant effect on integrated energy system performance. Specifically, as seen in Figure 4-2, thermal outputs are very low up to 40% of the

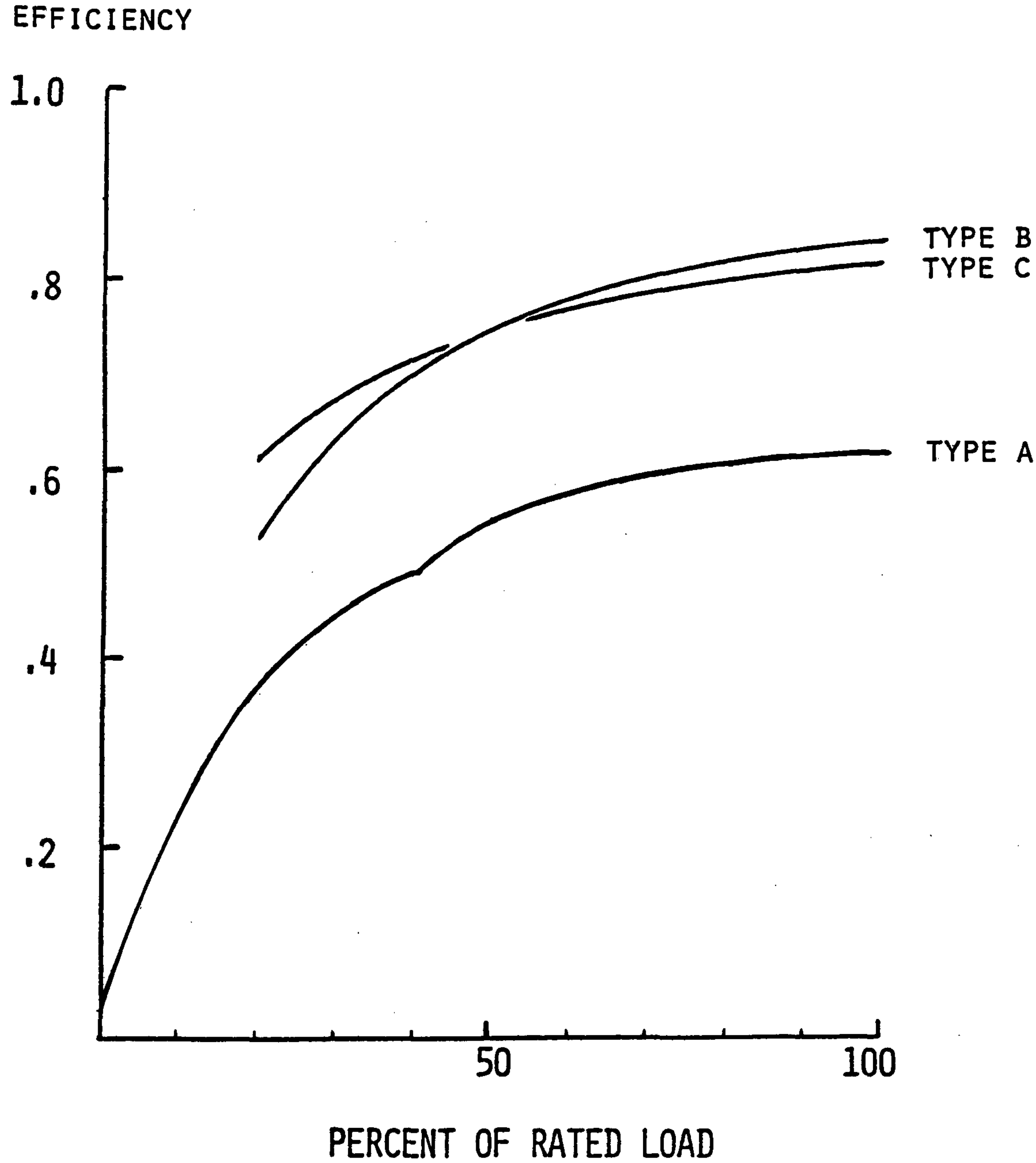


Figure 4-1. Combined Thermal and Electrical Efficiency. of Three Fuel Cell Types.

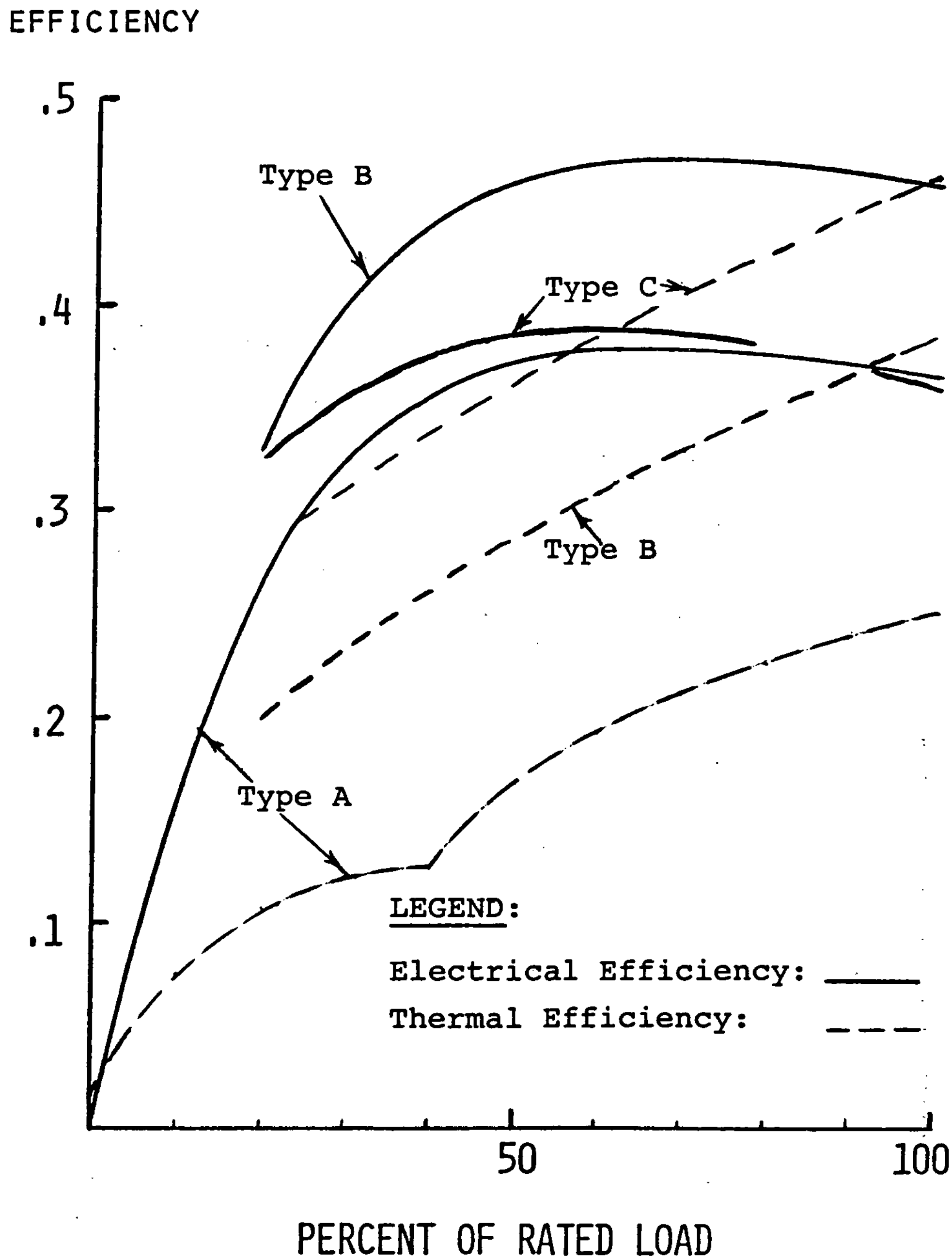


Figure 4-2. Electrical and Thermal Efficiency of Three Fuel Cell Types.

capacity. This results in less efficient operation for those applications where loads vary over a wide range.

4.3 Approach

Fuel cell systems were designed to maximize the use of the fuel cell and minimize the use of auxiliary furnaces or boilers. Although it would have been possible to choose a sufficiently large sized fuel cell to eliminate the need for an auxiliary boiler, this was not done for economic reasons. Similarly, the sizes of other supplementary equipment were chosen so as to obtain the best thermodynamic performance, while not jeopardizing the economics.

The system design process, which is illustrated in Figure 4-3, consists of four basic steps:

- definition of system configuration and operating equipment
- equipment sizing
- annual performance/evaluation
- system reliability analysis

First, a generalized system configuration was defined and operating guidelines were established to conform to the design criteria outlined above. Then, for each building in each location a number of alternative equipment sizings were selected to satisfy building energy demands. Subsequently, each of these system sizing alternatives was simulated for four typical days (one for each season) and its approximate thermal performance and annual energy consumption determined. Based on these data and a preliminary economic analysis, the most attractive system designs were selected for each building and location. Each selected design was then subjected to a detailed, 73-day simulation/evaluation to determine system and equipment performance levels for a typical weather year.

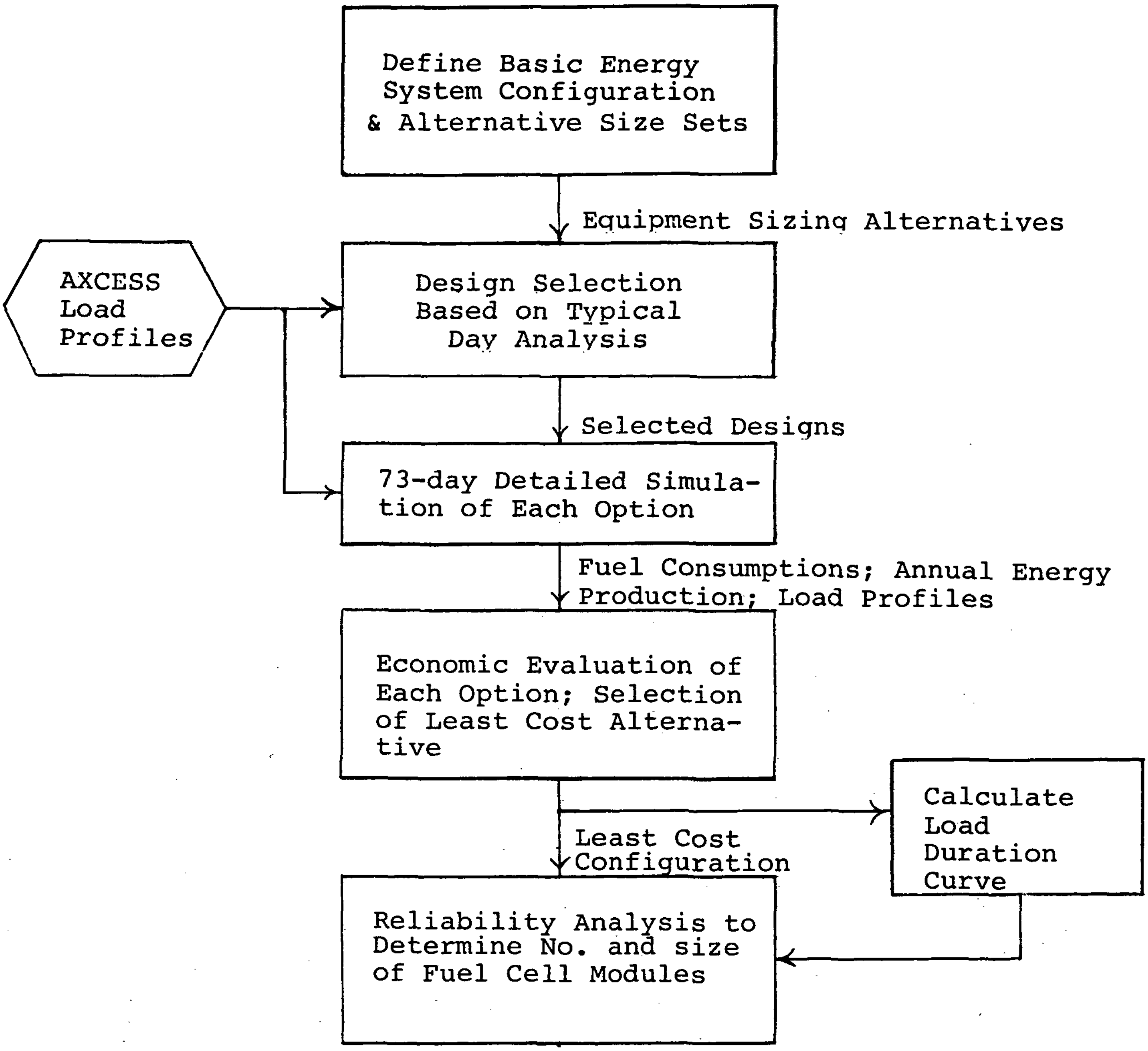


Figure 4-3. Design/Simulation Approach for OS/IES Without Utility Tie-In.

Once the sizing and evaluation steps were completed, a system reliability analysis was conducted to determine the optimum fuel cell module size and number of modules required to provide building electrical service with a reliability equivalent to that of typical electric utilities. Finally, the above fuel cell system designs were revised to include the appropriate numbers and sizes of fuel cells, and the design was complete.

Each of the above design steps is discussed in more detail below, in Section 4.3.1 and Sections 4.3.3 through 4.3.5. Section 4.3.2 describes the computer simulation that was developed for use in the system sizing and evaluation steps.

4.3.1 System Configuration and Operating Philosophy

A block diagram of the generalized on-site system design that was considered for each application and location is shown in Figure 4-4. The system includes a fuel cell, absorption chiller, vapor compression chiller, heat pump, electric resistance heaters, thermal energy storage, and a supplemental boiler.

A centralized system was chosen over a dispersed or unitary system for the secondary distribution system in order to make full use of the fuel cell's thermal energy for building heating, and cooling. Such a system is generally preferred for larger buildings because of its advantages in terms of equipment sizes and economics of scale. However, as Chapter 3 indicates, a unitary energy system is often employed in small apartment buildings, such as the one considered here, to take advantage of low-cost, standard equipment, and to reduce operating and maintenance overhead.

The general operating philosophy is as follows. Building electrical energy requirements are satisfied entirely by the fuel cell. Building requirements for space heat, hot water, and process steam (in the case of the hospital) are satisfied to the maximum extent

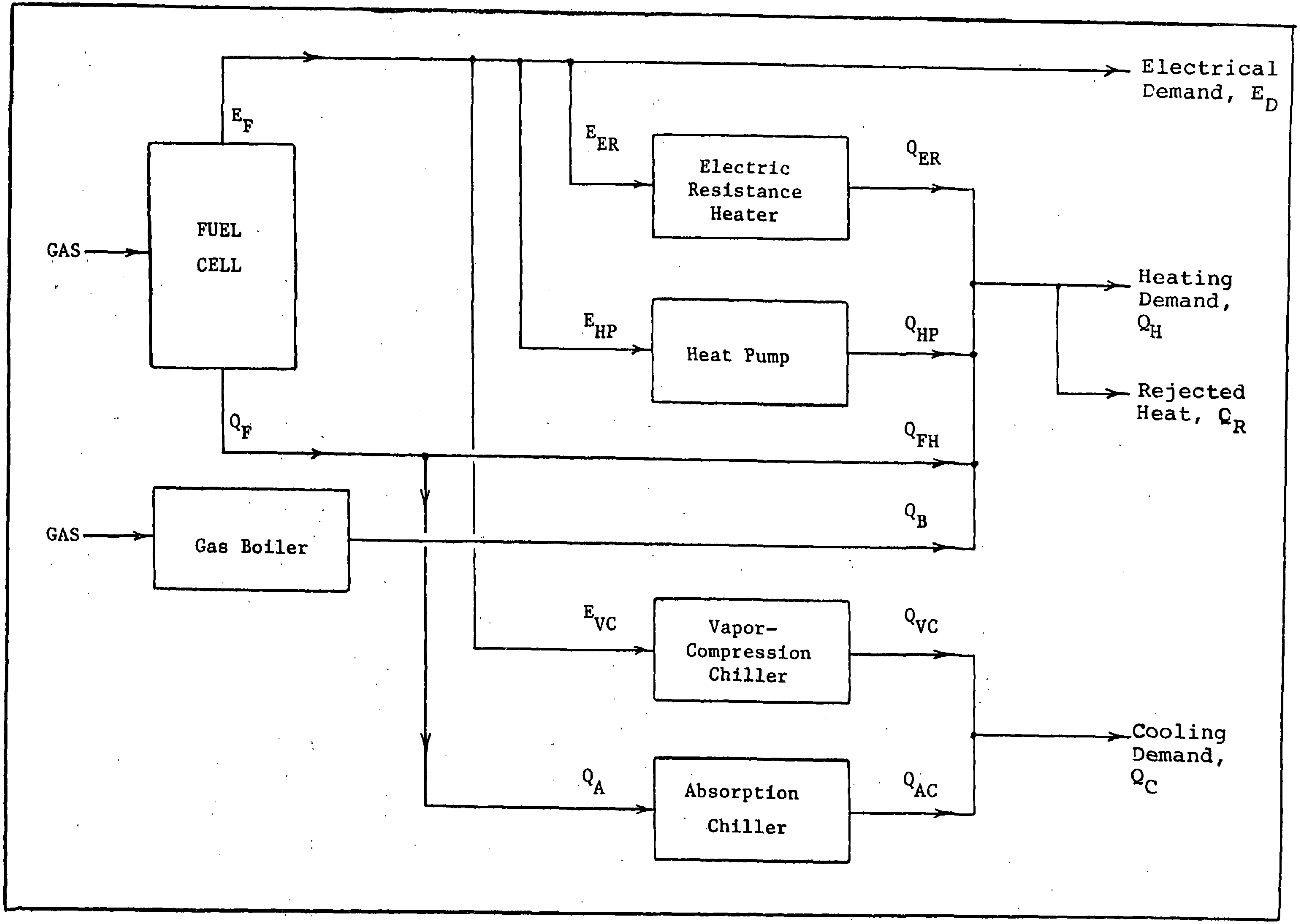


Figure 4-4. Generalized System Block Diagram

possible by the thermal energy available from the fuel cell.[1/] When the thermal energy available from the fuel cell is less than that required by the building, either the heat pump or the electric resistance heater is operated to satisfy an excess load. In a similar manner, the cooling demands of the building are first satisfied using heat from the fuel cell as input to an absorption chiller. When the available thermal energy is inadequate, or if the capacity of the absorption chiller is exceeded, an electric compression chiller is operated. In all situations, heat rejection by the on-site system is minimized. Only when the fuel cell's thermal and electrical capacity for heating or cooling is exceeded, is an auxiliary boiler operated to produce the required thermal energy.

4.3.2 System Simulation

As Figure 4-3 shows, a simulation model of the above generalized system was developed for use in the system sizing and evaluation steps. The computer simulation model that was developed for this purpose is based on the following four system equations:

$$E_F = (Q_{VC}/C_V) + (Q_{HP}/C_H) + (Q_{ER}/N_{ER}) + E_D \quad (4\text{-}1)$$

$$Q_F = T \cdot E_F = Q_{FH} + (Q_{AC}/C_A) \quad (4\text{-}2)$$

$$Q_H + Q_R = Q_{ER} + Q_{HP} + Q_{FH} + Q_B \quad (4\text{-}3)$$

$$Q_C = Q_{VC} + Q_{AC} \quad (4\text{-}4)$$

where:

E_F = electrical output of the fuel cell

Q_F = thermal output of the fuel cell

Q_H, Q_C, E_D = building heating, cooling, and electrical demands, respectively

Q_{VC}, Q_{AC} = cooling outputs of vapor compression and absorption chillers, respectively

---

1/ The energy requirements of the building will exactly match the energy quantities available from the fuel cell when the thermal-to-electric ratios (TER's) of the fuel cell and the load are the same and the fuel cell is appropriately sized to building electrical demand.

Q_{HP}, Q_{ER}, Q_B = heat outputs of heat pump, electric resistance heater and boiler, respectively

Q_{FH} = thermal energy from fuel cell that is not utilized by absorption chiller

Q_R = thermal energy from fuel cell that is not utilized

T = ratio of fuel cell thermal-to-electric outputs versus loading

C_H, C_V, C_A = coefficients of performance of heat pump, vapor compression chiller, and absorption chiller, respectively, versus loading

N_{ER} = efficiency of electric resistance heater

Although these four equations contain 11 variables, three of these are the building end-use demands, and many of the remaining eight are dependent on the selection of only a few equipment operating levels. In particular, at any given instant, the following equipment operating dependencies apply:

- once Q_{VC} is specified, Q_{AC} is also determined by Equation 4
- if Q_B is required, $Q_R = 0$; and similarly $Q_B = 0$ when Q_R is non-zero
- the electric resistance heater(s) will be used only when the heat pump (which is more efficient) is operating at capacity

In essence, the system scheduling task is one of selecting instantaneous values for Q_{VC} and either Q_{HP} or Q_{ER}, so as to minimize Q_R and Q_B. For those hours of the year when either Q_C or Q_H is zero, the optimum becomes a function of only one variable (typically Q_{VC} or Q_{HP}). The logical flow of the simulation procedure is described next.

The simulation proceeds, as shown in Figure 4-5, to calculate the state of the system for each hour of each day and to sum selected system inputs and outputs for inclusion in monthly and annual reports (or logs). As mentioned above, the system is operated throughout the year so as to meet all end-use loads, to maximize the use of fuel cell thermal energy and to minimize boiler use. For each hour optimum values are calculated for each of the four operating levels, Q_{ER}, Q_{HP}, Q_{VC}, and Q_{AC}, based on a linearized model[2/] in which the various equipment COP's are set at nominal (average values). Then, setting the four operating fractions at the above calculated values, non-linear equipment operating characteristics are substituted as appropriate for the constant COP's, and a more accurate determination is made of equipment input levels and, in turn, fuel cell loading and performance for the given hour. Any minor adjustments to equipment operating levels that are required at this point are made in accordance with the operating guidelines discussed in the previous section.

As Figure 4-5 indicates, the simulation program completely defines the state of the on-site system for each hour of each simulated day. However, very little of this hourly information is explicity reported by the simulation. Instead, the hourly information is summarized in monthly and annual logs and plotted in equipment load duration curves for use of analysis. Hourly values are reported, however, for the fuel cell electric output. Sections 4.3.3 and 4.3.4 describe the use of this simulation for system sizing and annual performance evaluation, respectively, and Section 4.3.4 provides a set of sample results for a specific application, location and fuel cell type.

[2/] It is not necessary to use a linearized state model in arriving at optimum operating fractions. However, optimization of the non-linear system model would require a more complex iterative solution for each hour, and the approximate approach seemed to provide adequate, near-optimal results.

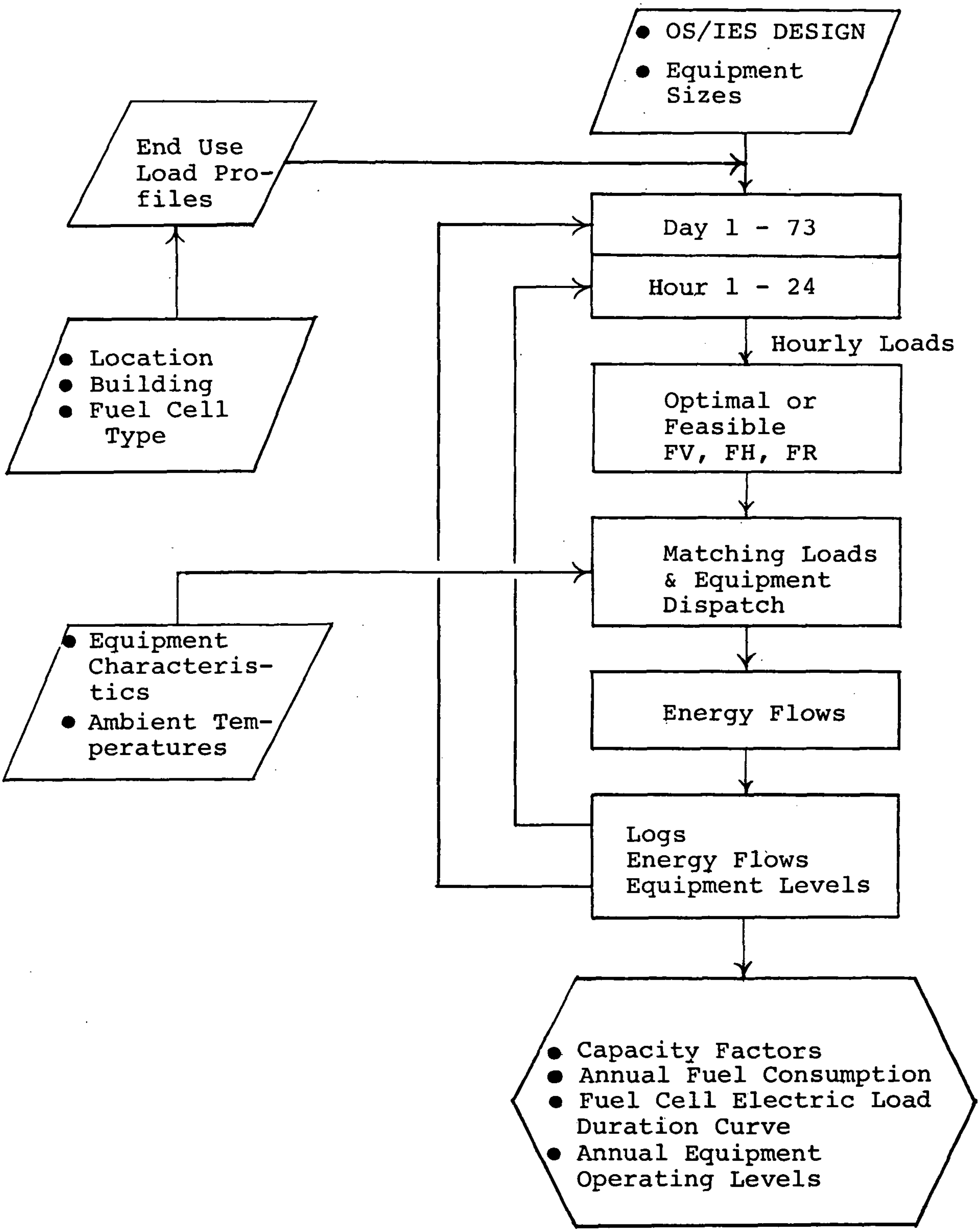


Figure 4-5. Flow diagram for Simulation Programs

4.3.3 Use of Simulation for Equipment Sizing

One goal of the design process was to minimize system life cycle costs. However, formal mathematical optimization was beyond the scope of the study. Therefore, a set of sizing alternatives was specified for each building/location/fuel cell combination, and the alternative with the lowest approximate life cycle cost was selected for detailed evaluation.

Figure 4-6 illustrates the sizing procedure. As the figure shows, for each building/location/fuel cell combination a number of alternative sizing sets are specified, based on the conventional system equipment sizes and design day load profiles as produced by the AXCESS program. Each sizing set consists of a set of maximum capacities for each of the major equipment items shown in Figure 4-4 (plus a cooling tower for the cooling system). The approximate annual performance of the on-site fuel cell system is then simulated for each of the alternative sizing sets over four typical seasonal days provided by AXCESS.[3/] Based on the simulation results, annual operation, maintenance, and fuel costs are estimated for each sizing alternative. Levelized fixed costs also are estimated, based on an assumed fixed charge rate and preliminary capital cost estimates for each set of equipment sized. These levelized fixed costs are then added to the annual production costs to give a comparative measure of system life cycle costs for each sizing alternative. Cost estimates for each alternative are then compared, the lowest cost sizing alternative is selected, and all major equipment is sized accordingly. The total fuel cell capacity also is fixed at this point, with the understanding that the fuel cell design will be revised somewhat, as a result of the reliability analysis

[3/] The four typical days were selected out of the 73 days simulated by AXCESS. For each season, the typical day that was chosen had an average temperature very close to the seasonal average temperature for that location and weather year.

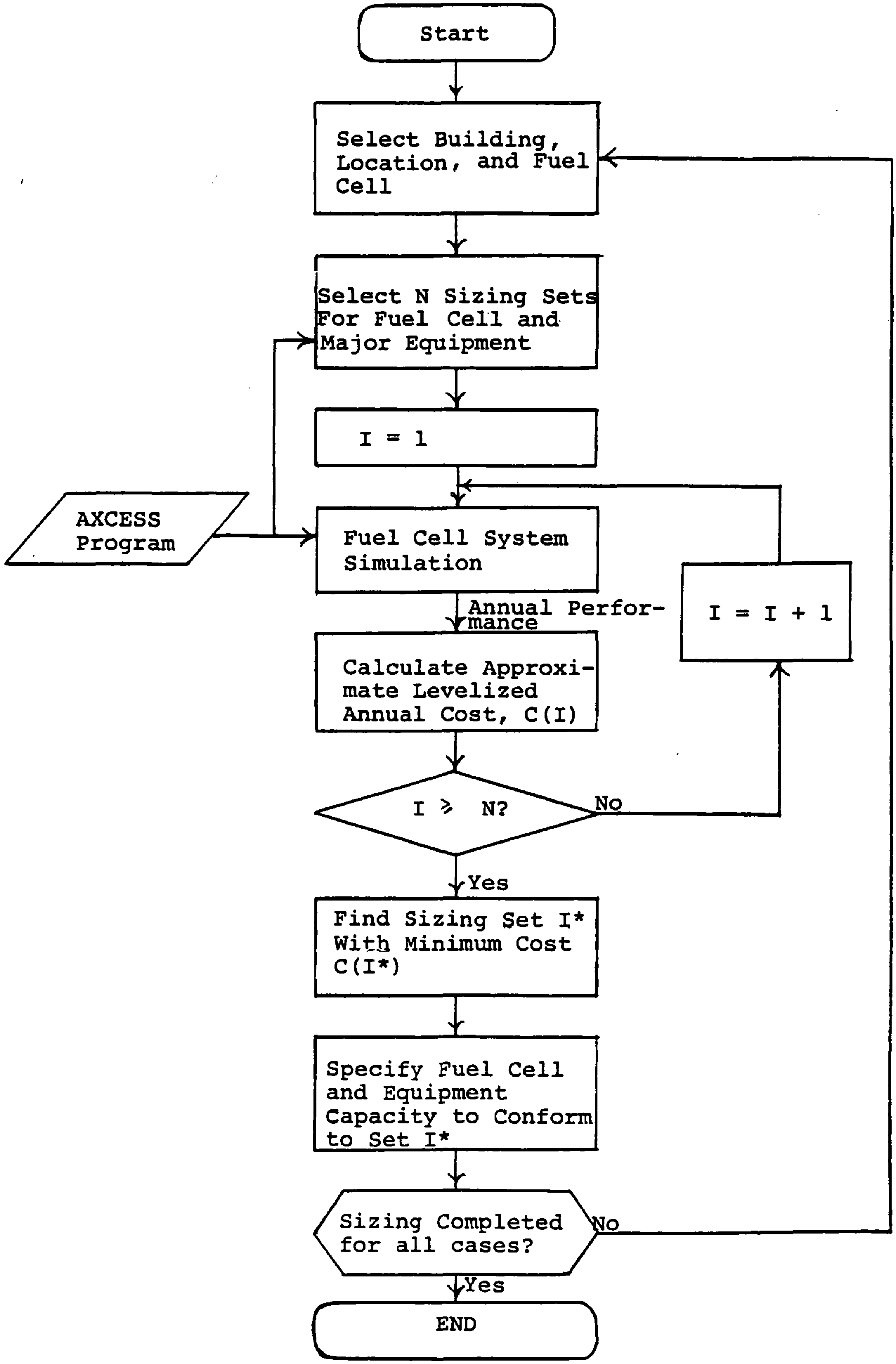


Figure 4-6. Use of Simulation For Sizing Analysis

in order to provide modularity and a certain amount of reserve capacity. The above process is repeated for each of the 27 building/location/ fuel cell combinations.

Table 4-1 provides sample results of the above sizing process for a hospital in Washington, D.C., with a Type B fuel cell system. As the results show, a number of heating and cooling alternatives were investigated with the major tradeoffs occurring between electrically- and thermally-based heating and cooling technologies. A range of fuel cell sizes also were investigated. Reducing fuel cell size generally reduced life cycle cost, until the point at which electrical heating and cooling equipment operation was constrained by the unavailability of electricity. At that point, boiler use increased, and the attendant fuel cost increases offset the incremental savings in fuel cell capital cost. As Table 4-1 shows, Design Set #5 was the lowest cost alternative for this building/location/fuel cell combination. Equipment sizes for other buildings, locations, and fuel cells were determined similarly.

4.3.4 Use of Simulation for Annual Performance Evaluation

Once equipment sizings were selected for each of the OS/IES fuel cell systems, the performance of each system was evaluated over 1752 hours of an actual weather year, using the simulation described in Section 4.3.2. Figure 4-7 shows the major inputs and outputs required by the simulation for this evaluation step. In addition to the building, location and fuel cell type, these include:

- fuel cell and equipment capacities from sizing analysis
- hourly end-use load profiles for 73 days from AXCESS program
- fuel cell performance characteristics (see Section 4.3.1)
- HVAC equipment performance characteristics (refer to Appendix F)

TABLE 4-1

FUEL CELL SYSTEM COST COMPARISON FOR ALTERNATIVE SIZE SETS

(TYPE B FUEL SYSTEM FOR HOSPITAL, WASHINGTON, D.C.

ITEM	DESIGN NUMBER							
	1	2	3	4	5	6	7	8
Fuel Cell Size, kW_e	1600	1500	1200	1200	1200	1200	1200	1000
VC Chiller Size, kW_t	1056	1056	1232	1056	704	1056	1144	1056
AC Chiller Size, kW_t	1232	1056	880	1056	1056	104	968	1056
Heat Pump Size, kW_t	39.6	35.20	31.68	29.92	26.40	26.40	24.64	26.40
Elec. Resist Size, kW_e	90	80	70	60	45	45	40	45
Fuel Cell Cost, 1000 $	442.0	416.2	338.2	338.2	338.2	338.2	338.2	285.5
HVAC Equipment Cost*, 1000 $	247.4	228.1	222.8	213.2	180.8	190.2	200.8	203.2
Total Cost, 1000 $	689.4	644.3	561.0	551.4	519.0	528.4	539.0	488.7
Annual Fixed Charge, 1000 $	92.4	86.3	75.2	73.9	69.5	70.8	72.2	65.5
Gas Cost, 1000 $	214.1	204.0	208.3	205.1	195.4	205.6	215.2	206.9
O & M, 1000 $	62.3	59.2	59.6	58.6	55.2	58.1	60.4	55.2
Total Annual Cost, 1000 $	368.8	349.5	343.1	337.6	320.1	334.5	347.8	327.6

* Capital costs for all design sets include the cost of a 1000 MBH boiler. Exact boiler size was determined subsequent to detailed simulation, based on system requirements for excess thermal energy.

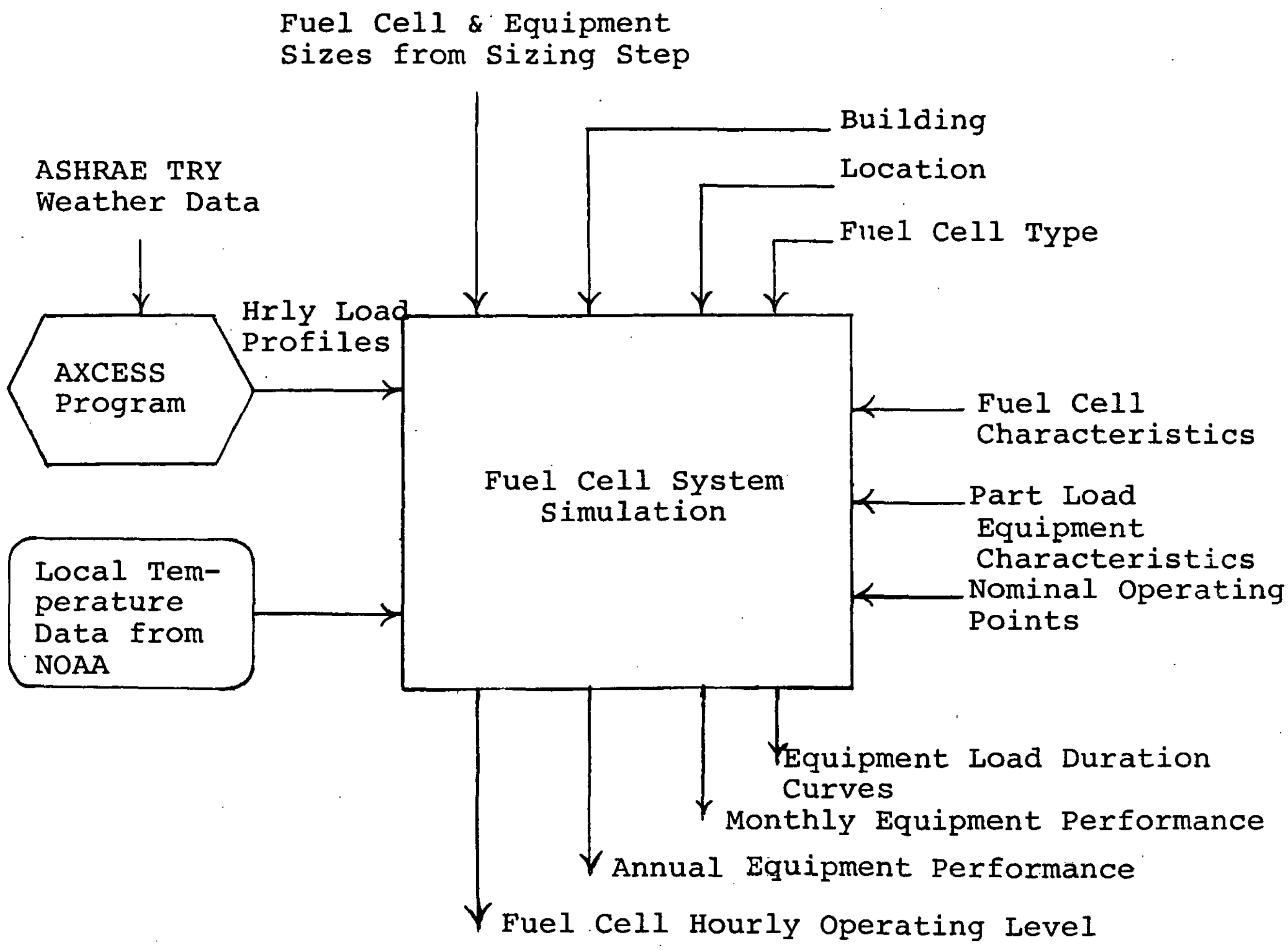


Figure 4-7. Use of Simulation for Annual Performance Evaluation

- nominal equipment operating points for equipment dispatch optimization (discussed in Section 4.3.2)
- temperature profiles by location from the National Oceanic and Atmospheric Administration (NOAA)

Input/output characteristics for those HVAC equipment items (including heat pump, vapor compression chiller, and absorption chiller) whose performance was assumed to vary with load or temperature, are described in Appendix F. Although ambient temperatures were available from NOAA for every hour of the ASHRAE Test Reference Years (described previously in Chapter 1), only the temperatures for every third hour of the appropriate days was provided to the simulation in order to reduce input data requirements. Temperatures for intermediate hours were then calculated from the above temperatures by straight-line interpolation.

As Figure 4-7 indicates, the simulation produces four separate classes of system performance information. First, the state of the fuel cell (in terms of electrical output) is completely documented for every hour of each day simulated. This permits the exact times, frequencies, and durations of daily and annual peak and minimum loadings on the fuel cell to be determined and/or quantified. Table 4-2 shows a sample of such data for the Type B fuel cell system designed for the hospital building in Washington, D.C. Monthly and annual equipment performance information is also produced, as illustrated by Tables 4-3, and 4-4 for the same hospital system. This information primarily is composed of total monthly (or annual) energy inputs and outputs to each major equipment item. Using these results, it is possible to construct a complete electrical and thermal breakdown for each month or the entire year. Alternatively, it is possible to analyze the monthly or annual performance of any specific equipment item, e.g., the vapor compression chiller. Finally, the simulation produces annual load duration curves (statistical pictures of equipment operating level over the year) for each

TABLE 4-2

FUEL CELL ELECTRIC OUTPUT BY HOUR OF DAY, KW

DAY	HOUR OF DAY											
	1 13	2 14	3 15	4 16	5 17	6 18	7 19	8 20	9 21	10 22	11 23	12 24
5	990.2 1164.4	994.2 1171.9	1000.5 1182.5	1007.6 1172.7	1016.7 1177.3	1041.8 1198.3	1200.0 1170.3	1200.0 1165.0	1195.3 1031.5	879.3 1029.6	888.4 1026.6	1180.3 1039.4
10	1048.0 974.6	1049.7 965.0	1049.7 969.1	1048.0 1200.0	1055.4 1200.0	844.1 1200.0	875.8 1200.0	1200.0 1200.0	901.7 1159.5	893.2 1080.6	968.9 1082.6	974.2 1089.4
15	1118.0 1200.0	1118.9 1200.0	1122.6 1200.0	1125.3 1200.0	1135.5 1200.0	1200.0 1200.0	1200.0 1200.0	1200.0 1200.0	1200.0 1200.0	1200.0 1130.1	1200.0 1129.1	1200.0 1129.1
20	1049.6 1181.9	1051.9 1167.4	1055.2 1180.0	1056.7 1164.0	1063.3 1169.6	1085.0 1187.8	1200.0 1156.4	1200.0 1149.3	1200.0 1013.3	1197.7 1010.1	1200.0 1007.1	1188.5 1016.1
25	1092.7 1200.0	1091.0 1200.0	1089.5 985.8	1088.8 1200.0	1095.8 982.5	1200.0 1200.0	1200.0 1200.0	1200.0 937.7	1200.0 1154.9	1200.0 1073.9	1200.0 1072.2	1200.0 1083.4
30	1036.8 1200.0	1040.8 1200.0	1044.5 976.7	1049.5 1200.0	1057.4 971.2	1165.6 968.4	1200.0 1200.0	1200.0 1200.0	970.1 1142.7	964.5 1062.4	990.9 1062.4	987.3 1072.4
35	652.7 1003.4	657.1 951.2	656.4 980.2	649.8 974.7	669.7 981.0	744.0 981.5	790.8 845.8	975.7 831.2	1004.7 756.2	988.5 719.5	1000.2 729.0	1013.0 742.0
40	985.6 843.8	987.2 805.5	989.5 761.2	990.1 864.7	996.4 918.0	1022.0 920.2	871.0 901.6	1189.5 701.8	831.9 583.2	818.7 574.8	836.6 743.5	828.4 688.6
45	1057.6 973.9	1062.4 957.6	1066.4 934.2	1065.9 1200.0	1072.6 904.1	1176.0 926.6	1200.0 929.2	1200.0 931.8	969.1 1148.4	960.[illegible]		
50	721.0 965.0	722.5 954.9	722.0 896.8	725.5 1200.0	732.8 874.5	838.7 900.8	889.8 927.5	966.7 906.4				
55	671.0 870.0	674.6 857.8	978.4 855.0	982.8 856.1	993.6 769.7	1021.6 784.7	875.6 772.8	[illegible]				
60	1061.2 980.1	1060.2 973.6	1061.2 956.6	1062.2 1200.0	1069.6 906.5	1175.4 902.9	1200[illegible] [illegible]					
65	1053.0 982.1	1055.0 964.5	1053.0 964.5	1053.0 980.5	1059.8 896.2	1165.0 895[illegible]						
70	1059.0 976.0	1063.0 962.9	1065.0 960.5	1066.2 972.3	1073.1 955.1							
75	511.9 880.3	521.7 871.3	598.6 874.6	616.5 864.7	643[illegible] 8[illegible]							
80	1041.6 975.0	1041.6 959.0	1042.6 960.6	1042.6 972.3								
85	1035.8 974.0	1036.4 973.9	1037.9 990.8	10[illegible]								
90	986.8 884.2	988.9 874.9	992.[illegible] 8[illegible]									
95	797.7 1022.6	797.7 10[illegible]										
100	574.[illegible]											

TABLE 4-3

ANNUAL ENERGY USE SUMMARY: WASHINGTON HOSPITAL, TYPE B FUEL CELL SYSTE

Building Requirements	
- Electric (including electric cooking), kWh	5,648,175
- Space Heating and DHW, kJ	15,008,780
- Space Cooling, kJ	17,629,942
- Gas Cooking, kJ	25,120,269
Total Gas Consumption OS/IES, kJ	67,383,108
Equipment Operation	

Equipment Item	INPUTS		OUTPUTS	
	Electrical, kWh	Thermal, kJ	Electrical, kWh	Thermal, kJ
Fuel Cell	---	61,495,392	7,966,745	2,099,350
Heat Pump	653,794	---	---	5,448,693
Electric Resistance Heater	116,828	---	---	412,053
Absorption Chiller	---	13,802,796	---	7,376,441
Vapor Compressor Chiller	1,547,979	---	---	8,163,042
Boiler	---	5,636,539	---	4,509,232

TABLE 4-4

OS/IES ENERGY SUMMARY FOR SELECTED MONTHS FOR WASHINGTON HOSPITAL AND TYPE B FUEL CELL SYSTEM

ENERGY FLOW	MONTH			
	JANUARY	APRIL	JULY	OCTOBER
Electrical, kWh$\times 10^3$				
- Building Requirement	458	460	494	453
- Produced by Fuel Cell	798	622	623	643
- Heat Pump Input	129	10	2	53
- Electric Resistance Heater Input	23	0	0	13
- Vapor Compression Chiller Input	189	152	127	125
Heating Related, kJ$\times 10^6$				
- Building Requirement	2734	573	349	1346
- Fuel Cell Heat Utilized	1322	1391	1591	1388
- Fuel Cell Heat Not Utilized	487	206	1591	1388
- Heat Pump Output	862	87	23	514
- Electric Resistance Heater Output	76	0	0	239
- Boiler Output	123	81	980	239
Cooling Related, kJ$\times 10^6$				
- Building Requirement	330	1115	2763	808
- Vapor Compression Chiller Output	264	631	1458	409
- Absorption Chiller Output	65	484	1306	399
- Absorption Chiller Input	148	987	2246	840
Gas Use, kJ$\times 10^6$				
- Total Gas Use	6387	987	2246	840
- Gas to Fuel Cell	6214	4793	4792	4957
- Gas to Boiler	153	101	1226	299
- Gas For Cooking	21	21	21	21

major equipment item. These load duration curves provide a useful summary of the extent to which a given equipment item was utilized in terms of both operating hours and level. A complete set of such load duration curves is shown in Figure 4-8 for the same hospital energy system referred to above. As the following section describes, the fuel cell load duration curve is a very important input to the system reliability analysis.

Fuel cell load duration curves for all 27 fuel cell on-site integrated energy systems are presented in Appendix G.

4.3.5 Reliability Analysis

The requirement to provide utility level electric service reliability was an important constraint in the design of fuel cell systems without a utility tie-in. In order to meet this constraint, it was necessary to specify a fuel cell plant with more reserve capacity and a larger number of fuel cell modules then would otherwise be required. The preliminary designs described in the previous section, for example, included only a single fuel cell, sized to the predicted annual peak demand. The specific objective of this reliability analysis was to determine the optimum fuel cell module size and number of modules required for each of these designs in order to provide electric service reliability equivalent to that of a typical electric utility. This section begins with a discussion of the reliability goal that was set for the on-site fuel cell systems and concludes with a description of the reliaiblity analysis approach and the results obtained for each system.

For the purposes of this study, an Electric Service Reliability Index (SRI) was defined as:

$$SRI = \frac{\text{Annual Energy Demand-Annual Demand Not Served}}{\text{Annual Energy Demand}} \times 100\% \qquad (4\text{-}5)$$

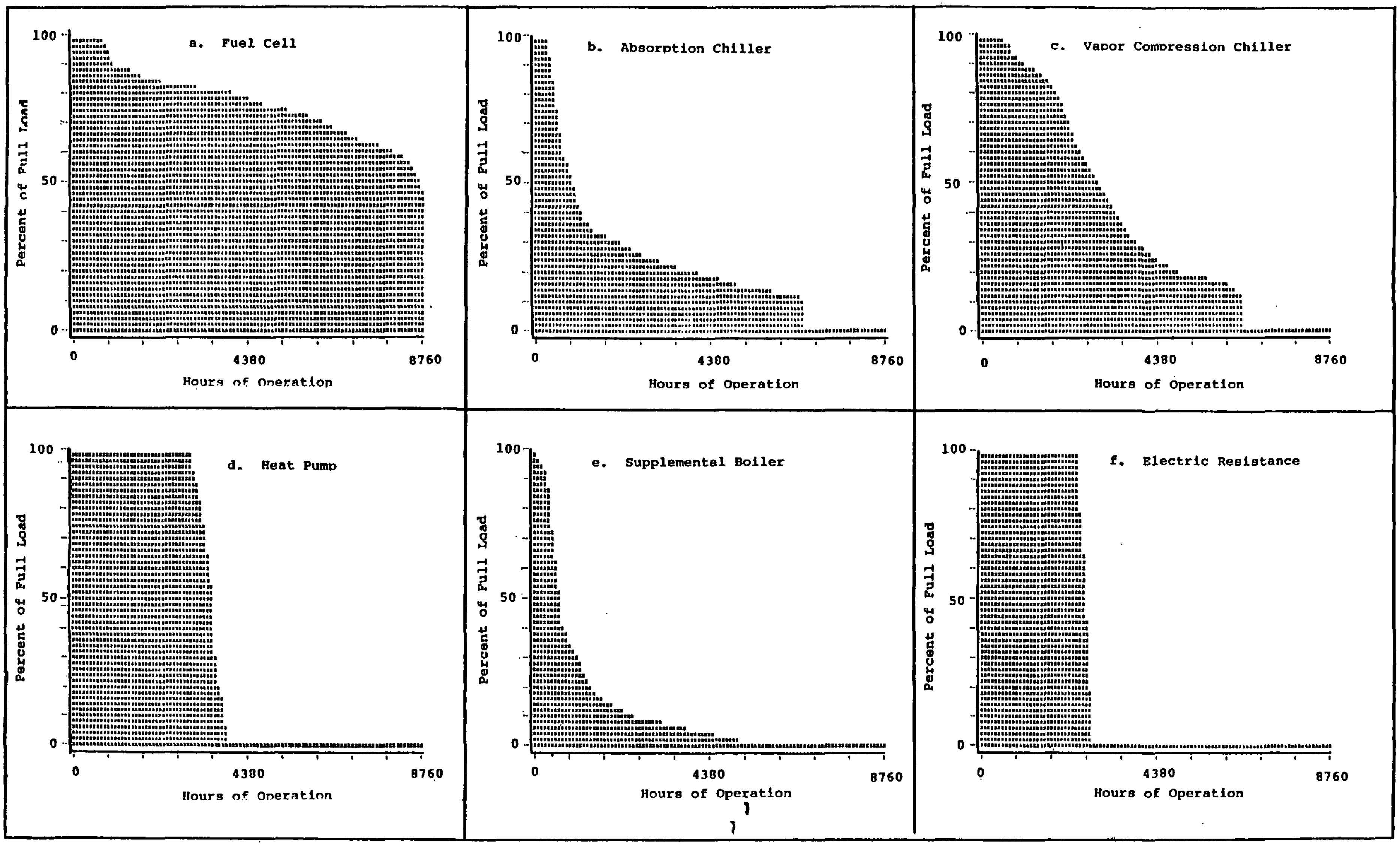


Figure 4-8. Equipment Load Duration Curves: Washington Hospital, Type B Fuel Cell System

The value of SRI, thus calculated for fuel cell OS/IES, was required to be approximately equal to (but not less than) 99.98 percent.

The method that was used to calculate SRI is an adaptation of conventional utility loss of energy approaches, and it relates the probabilities of operating in each of various fuel cell system capacity states to the annual load shape reflected at the fuel cell to determine the probabilistic magnitude of the annual energy requirement not served. This approach assumes that as long as one or more fuel cell modules are operational, some portion of the building energy demand can be met by these modules. Implicitly, therefore, the on-site fuel cell system was assumed to include some kind of load shedding hardware.[4/] It was assumed in all cases that each of the component fuel cell modules (regardless of size) had a forced outage of three percent. A simplified example of a loss of energy probability calculation is presented in Appendix H.

In determining the optimum module size and number of modules for each fuel cell system designed, a cost trade-off was made between a large number of modules with a small reserve margin and fewer modules with a larger reserve margin. As Figure 4-9 illustrates, a simple search approach was employed to find the lowest cost module set that would meet the reliability goal. It was assumed that each fuel cell system included three or more identical modules[5/] of the minimum size required to assure a service reliability of 99.98 percent. For each assumed module set, the required module size and fuel cell installed

---

4/ Load shedding hardware would consist primarily of the sensors and relays necessary to direct whatever fuel cell power is available to those circuits serving the highest priority loads and to additional circuits in descending order of priority. The costs of such hardware were assessed in this study, but were found to be negligible relative to other costs associated with the on-siste systems.

5/ The specified reliability goal could not be met with fewer than three modules regardless of their size.

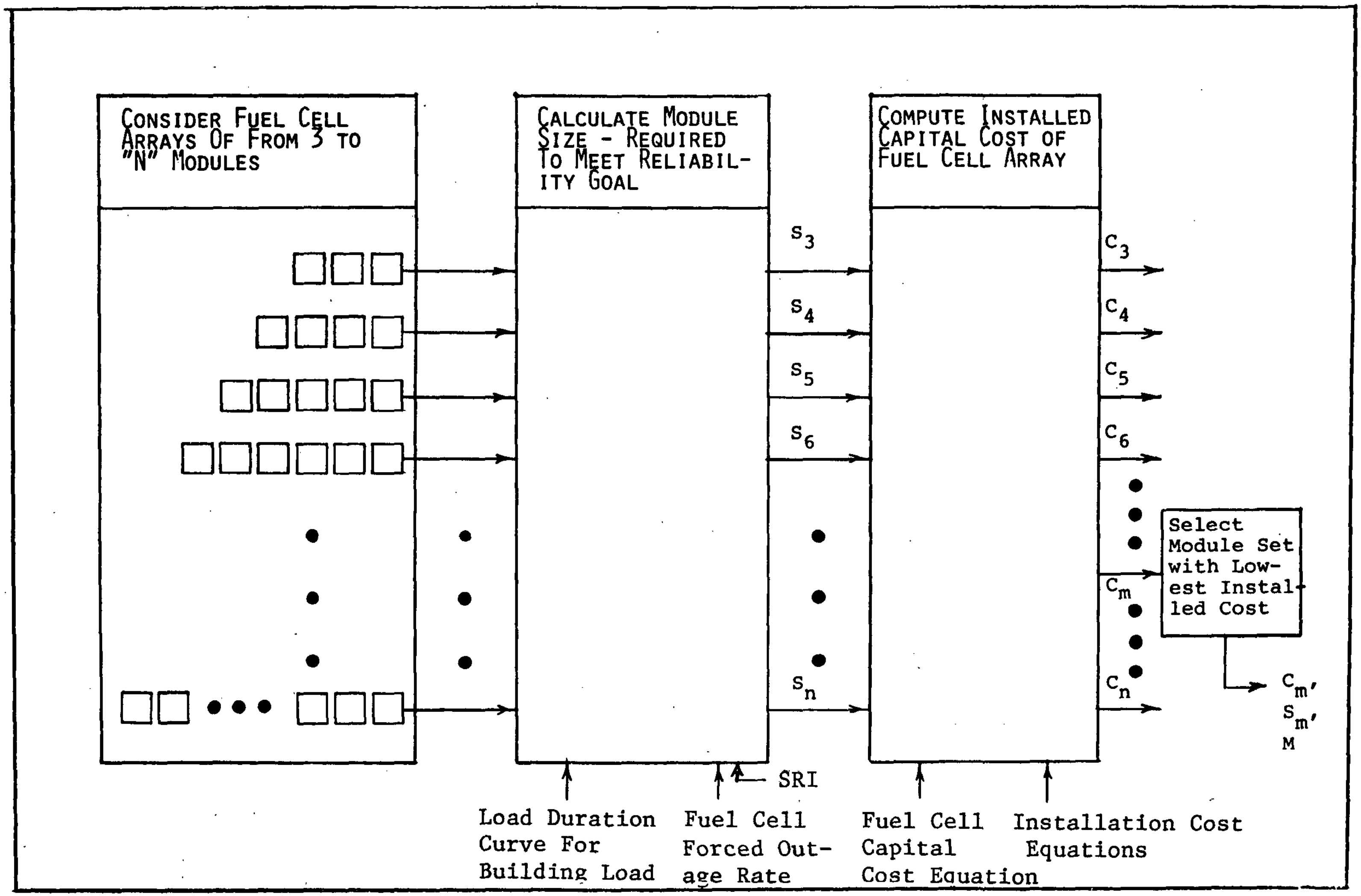


Figure 4-9. Selection of Fuel Cell Module Size and Number of Modules

capital costs were then calculated. Starting with three modules, the assumed number of modules was continually incremented until a minimum installed capital cost was reached. Final fuel cell plants were defined in this way for each building in each location, and the results are presented in Table 4-5.

The hospital application was somewhat unique in that a hospital generally has an emergency back-up power supply (i.e., a diesel-generator set) that is intended to provide increased reliability to "critical" loads. Therefore, the hospital fuel cell OS/IES system was required to match the reliability of a conventional utility supply system plus an on-site emergency back-up supply system. System reliability for the hospital application was analyzed in two steps. First, the hospital was analyzed as described above with the other building applications, solving for fuel cell system designs to meet the entire hospital energy requirement with a reliability equivalent to the conventional utility supply (SRI = 99.98). Second, the ability of the resultant fuel cell systems to supply that portion of the hospital load termed the "critical load" was evaluated with respect to the conventional utility/diesel combination supply. Again, the "loss-of-energy" approach was used. The target SRI for the critical load was calculated by mathematically combining the utility supply with its SRI of 99.98 with an emergency back-up system. For this analysis, it was assumed that the critical load is 40 percent of the peak building load (continuous) and that the emergency back-up system was composed of one diesel-generator with a rated capacity equal to the building critical load and with a forced outage rate of five percent. The calculated combined SRI yardstick for the hospital critical load was thus 99.999. The analysis showed that in all applications the fuel cell OS/IES designs containing four or more modules easily complied with the reliability design goal (SRI = 99.999) for the supply to the critical load. Since all of the minimum cost module sets selected in the first step contained more than four modules, the critical load reliability goal was satisfied in every case.

TABLE 4-5

OPTIMUM MODULE SIZE AND NUMBER OF MODULES FOR FUEL CELL SYSTEM WITHOUT UTILITY TIE-IN

BUILDING	LOCATION	FUEL CELL TYPE	MODULE SIZE (KW)	NUMBER of MODULES	TOTAL FUEL CELL CAPACITY (KW)	PERCENT RESERVE
Low-Rise Apartment	Chicago	A	6	12	72	20
		B	6	12	72	20
		C	6	12	72	20
	Dallas	A	6	12	72	20
		B	6	12	72	20
		C	6	12	72	20
	Washington, DC	A	6	12	72	20
		B	6	12	72	20
		C	6	12	72	20
Retail Store	Chicago	A	60	12	720	15
		B	55	13	715	14
		C	67	11	737	17
	Dallas	A	61	12	732	19
		B	61	12	732	18
		C	48	15	720	13
	Washington, DC	A	67	11	737	18
		B	61	12	732	17
		C	56	13	728	15
Hospital	Chicago	A	120	11	1320	18
		B	100	14	1400	17
		C	120	11	1320	18
	Dallas	A	100	14	1400	17
		B	140	10	1400	17
		C	140	10	1400	22
	Washington, DC	A	130	11	1430	19
		B	100	14	1400	17
		C	130	11	1430	19

4.4 Final Fuel Cell System Designs

Based on the equipment sizes determined in the sizing analysis, the boiler sizes determined from the simulation results, and the fuel cell design from the reliability analysis, final designs were developed for all 27 building/location/fuel cell combinations. Table 4-6 summarizes the sizes and annual load factors for the major equipment used in the Washington, D.C. on-site systems which include a Type "C" fuel cell. Fuel cell load factors for the apartment building and hospital are about double that of the retail store, while load factors for all equipment items are significantly higher for the hospital than either of the other two applications. Mechanical and electrical schematics also were developed for each system, and examples are shown in Figures 4-10 through 4-18 for the on-site systems summarized in Table 4-6 above. Equipment lists for all fuel cell systems are included in Appendix I.

References

1. Federal Power Commission, 1970 National Power Survey, Washington, D.C.

TABLE 4-6

OS/IES DESIGN SIZES VS. APPLICATION (VALUES FOR WASHINGTON, D.C. - FUEL CELL TYPE B)

Equipment Item	Residential		Retail Store		Hospital	
	Size	L.F.(%)	Size	L.F.(%)	Size	L.F.(%)
Fuel Cell, kW	72	65	720	35	1430	72
Heat Pump, kW	29.3	5.6	87.9	3.5	263.7	16.4
V.C. Chiller, kW	70.4	59.8	352	63.4	352	130.2
ABS Chiller, kW	105.6	38.7	880	38.7	1408	77.4
E.R. Heater, kW	20	0.34	40	1.3	70	34
Boiler, kW	73.2	2.9	805.8	1.3	1238	4.1

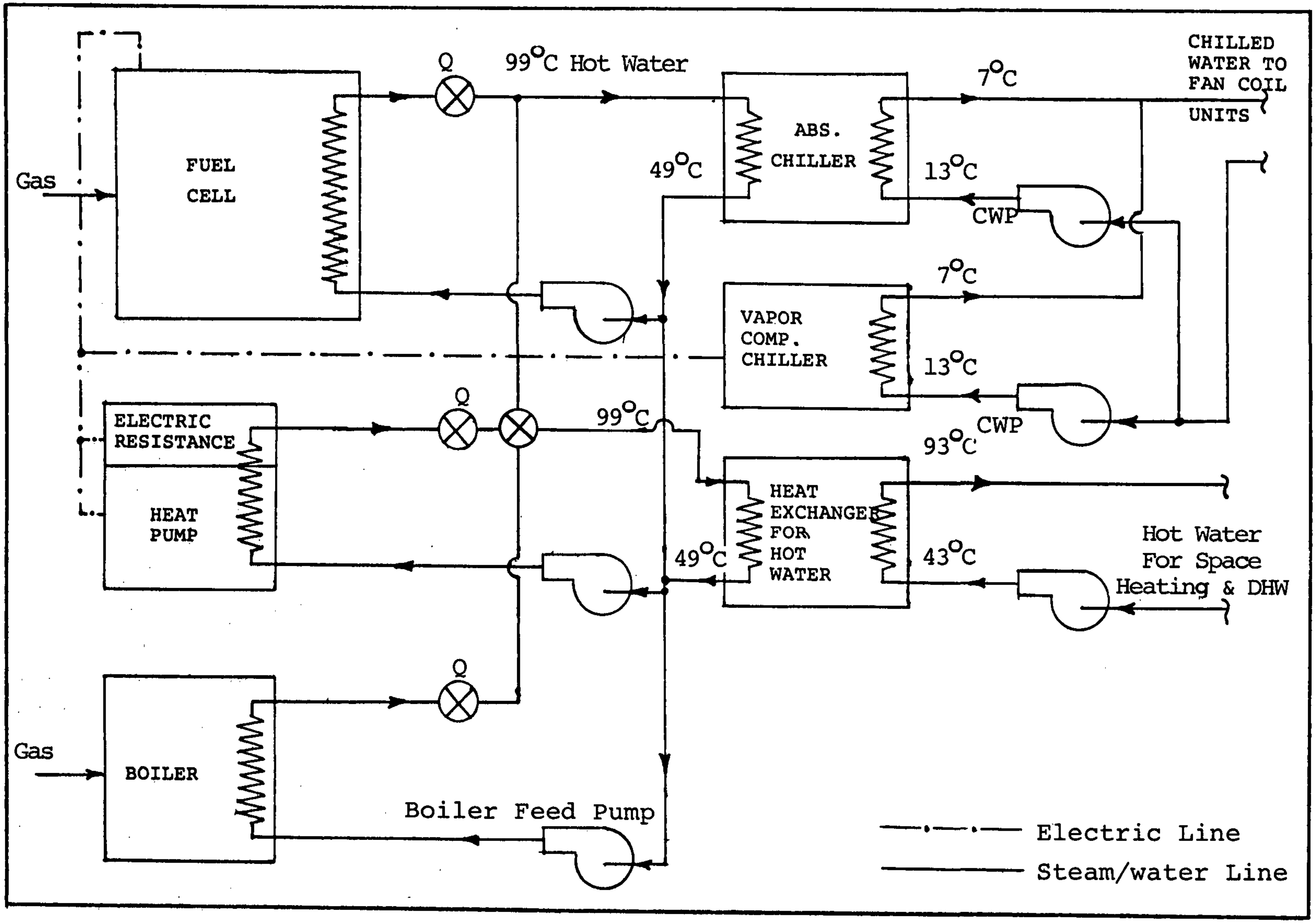


Figure 4-10. Apartment Building OS/IES Primary System (see Table I-1 for Equipment Sizes)

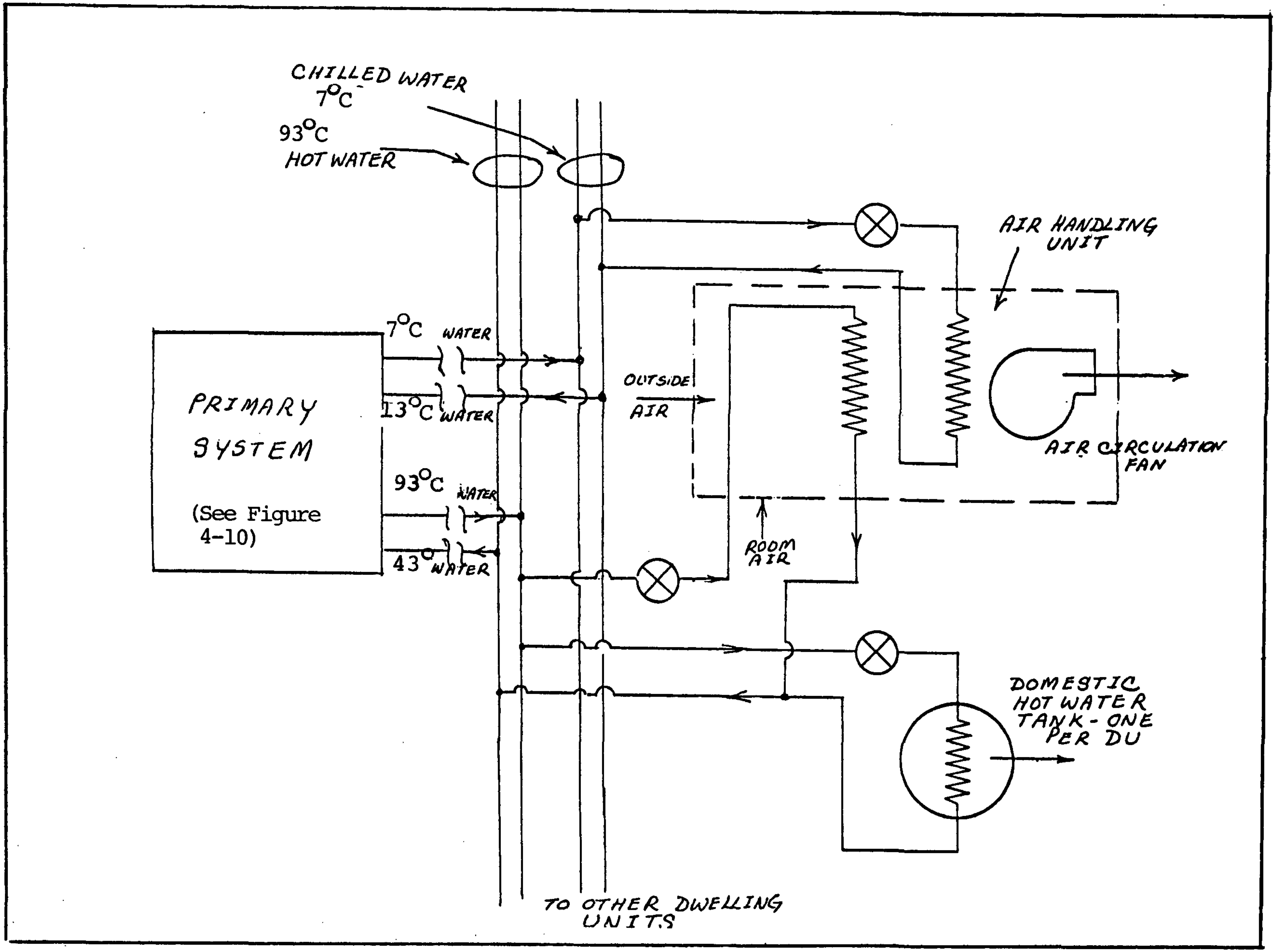


Figure 4-11. Apartment Building. Secondary System.

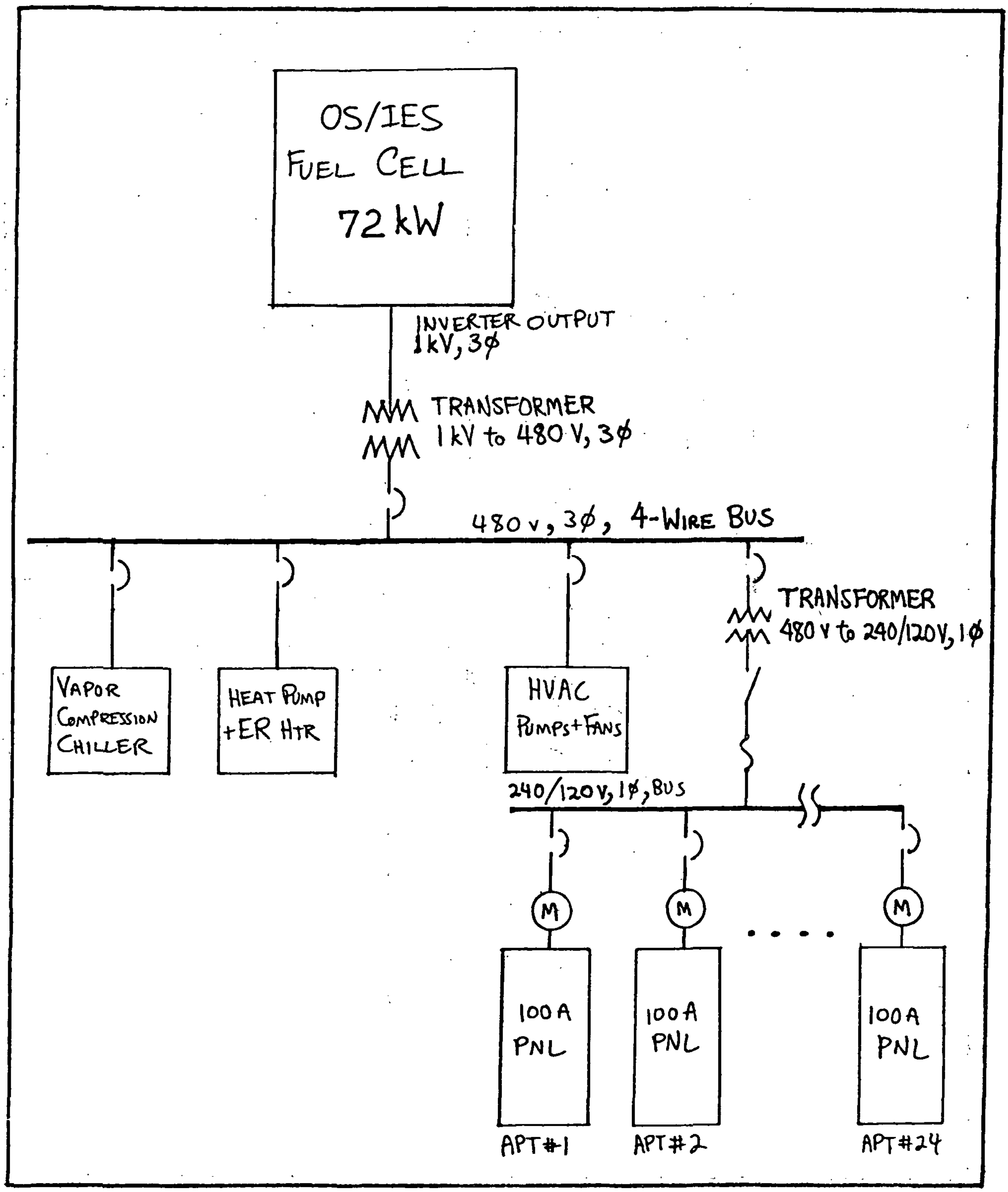


Figure 4-12. Electrical Service Schematic Apartment Building, Application; Washington, D. C.

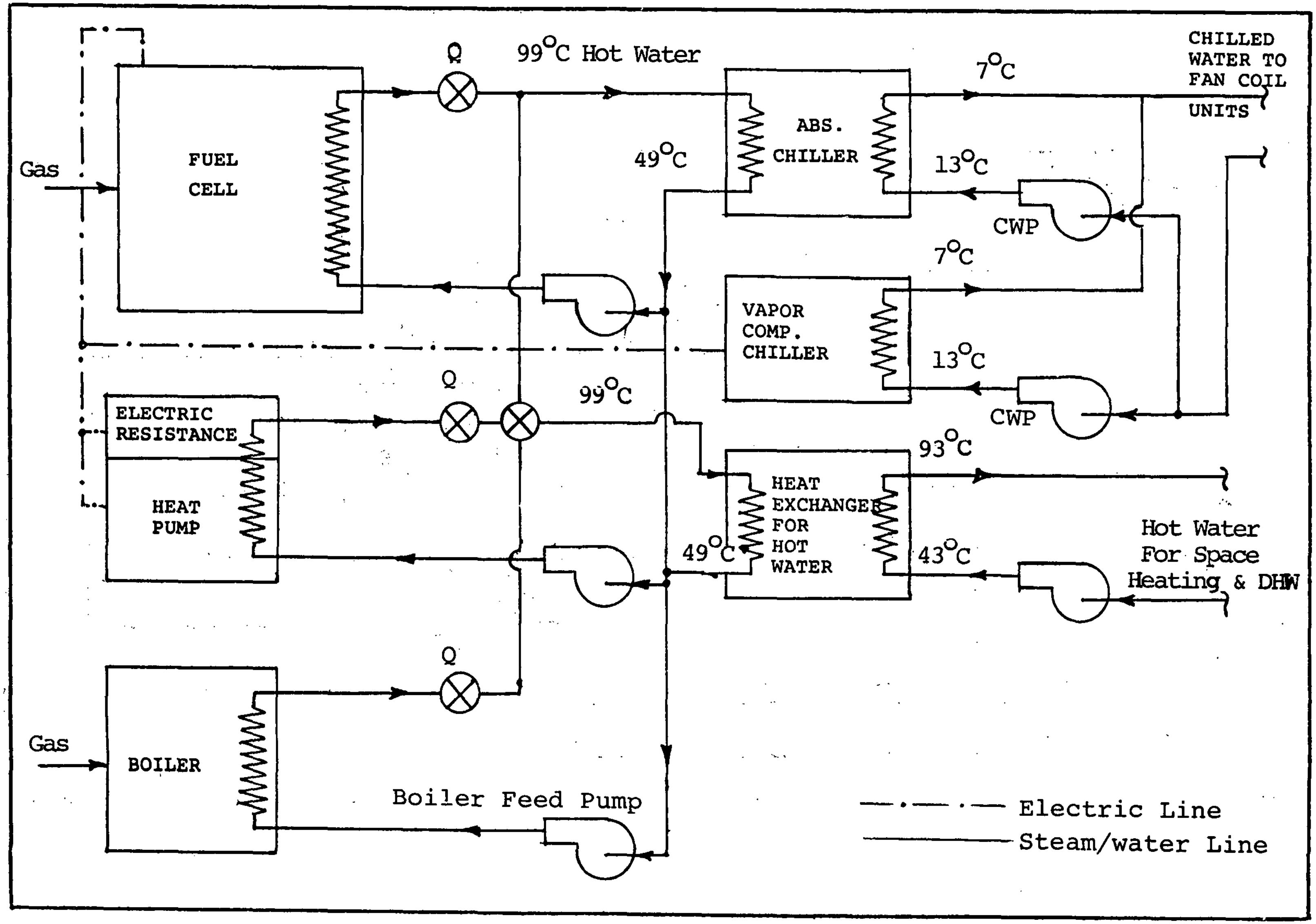


Figure 4-13. Retail store OS/IES Primary System (see Table I-2 for Equipment Sizes)

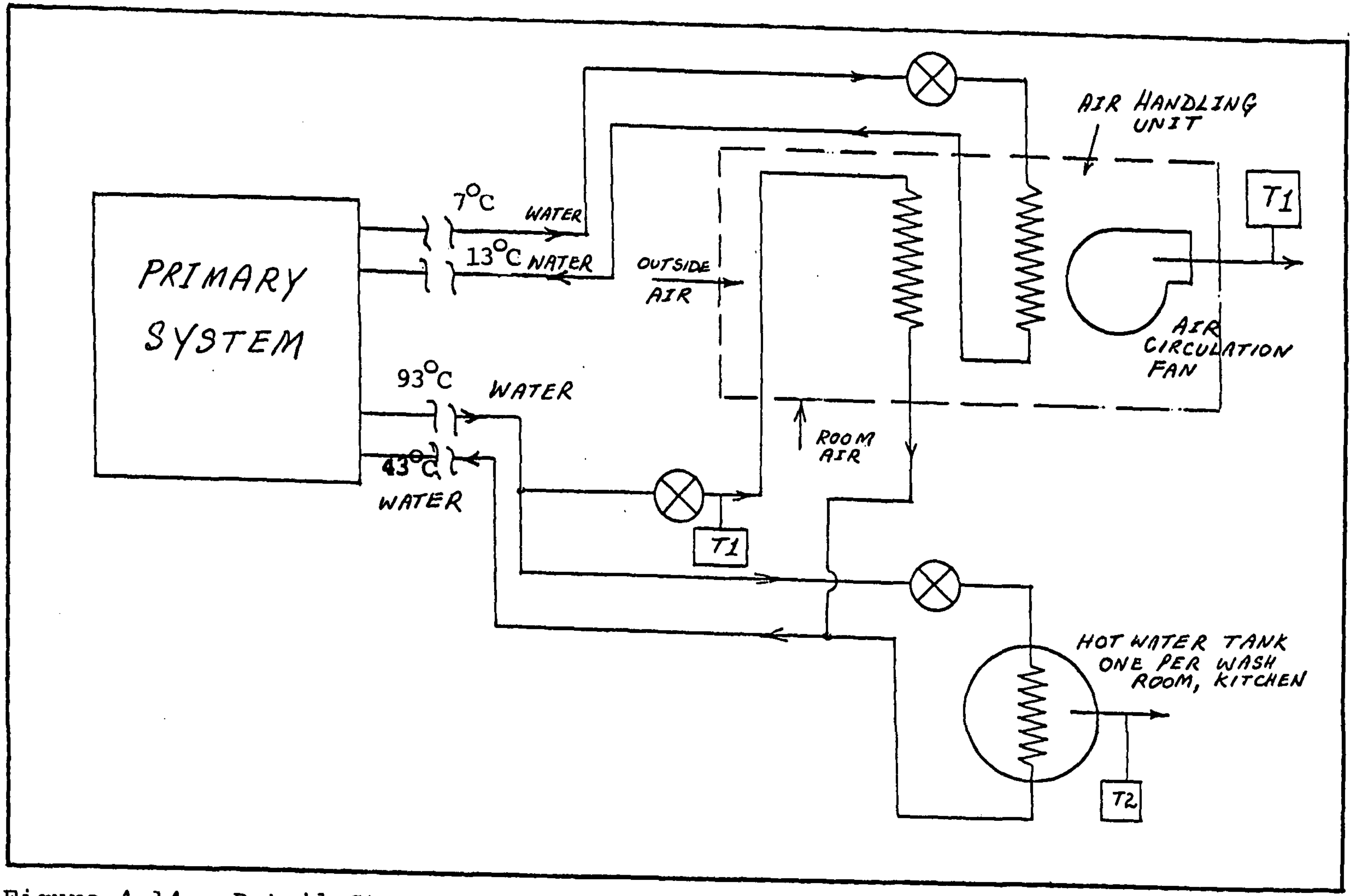


Figure 4-14. Retail Store Secondary System

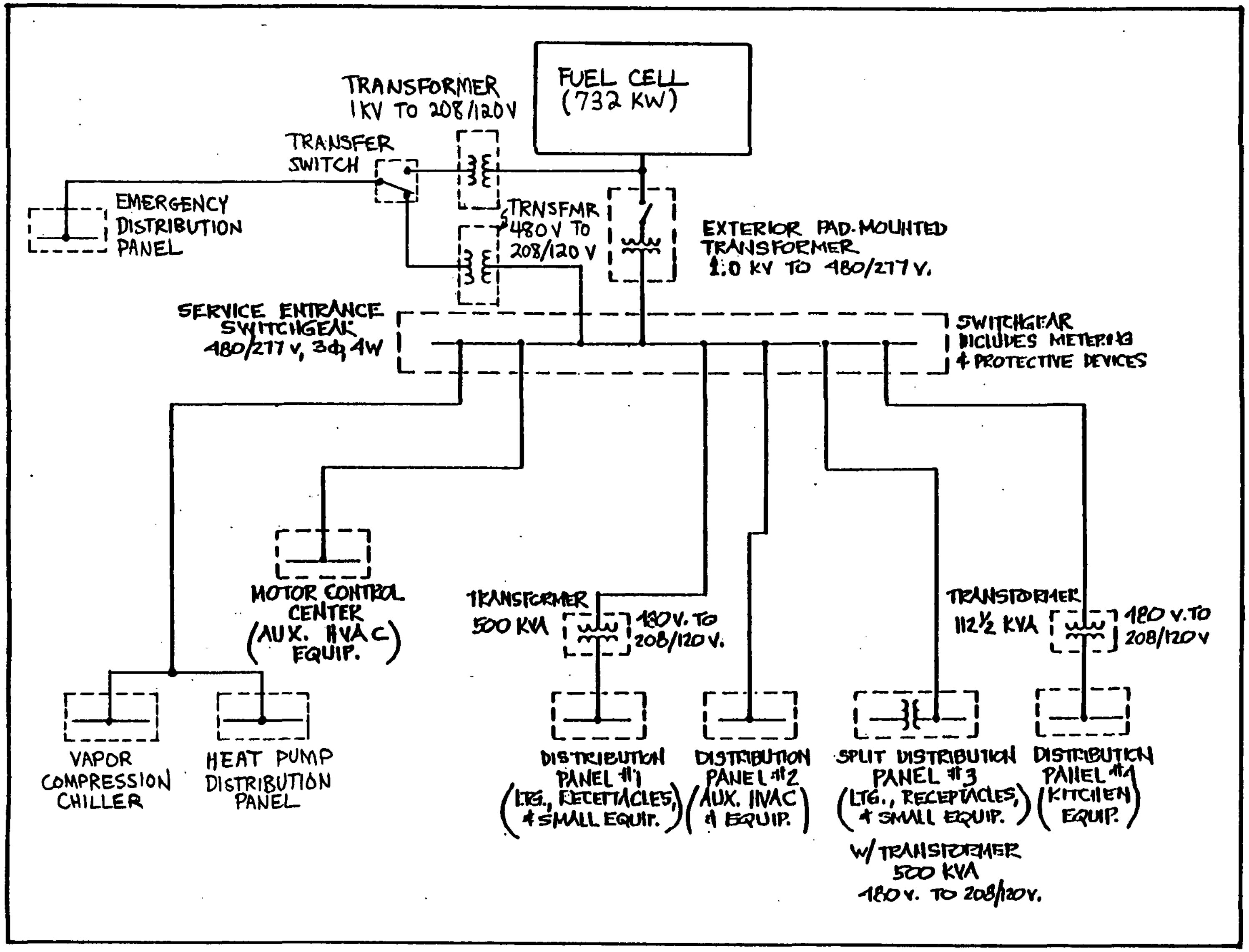


Figure 4-15. Electrical Service Schematic, Retail Store

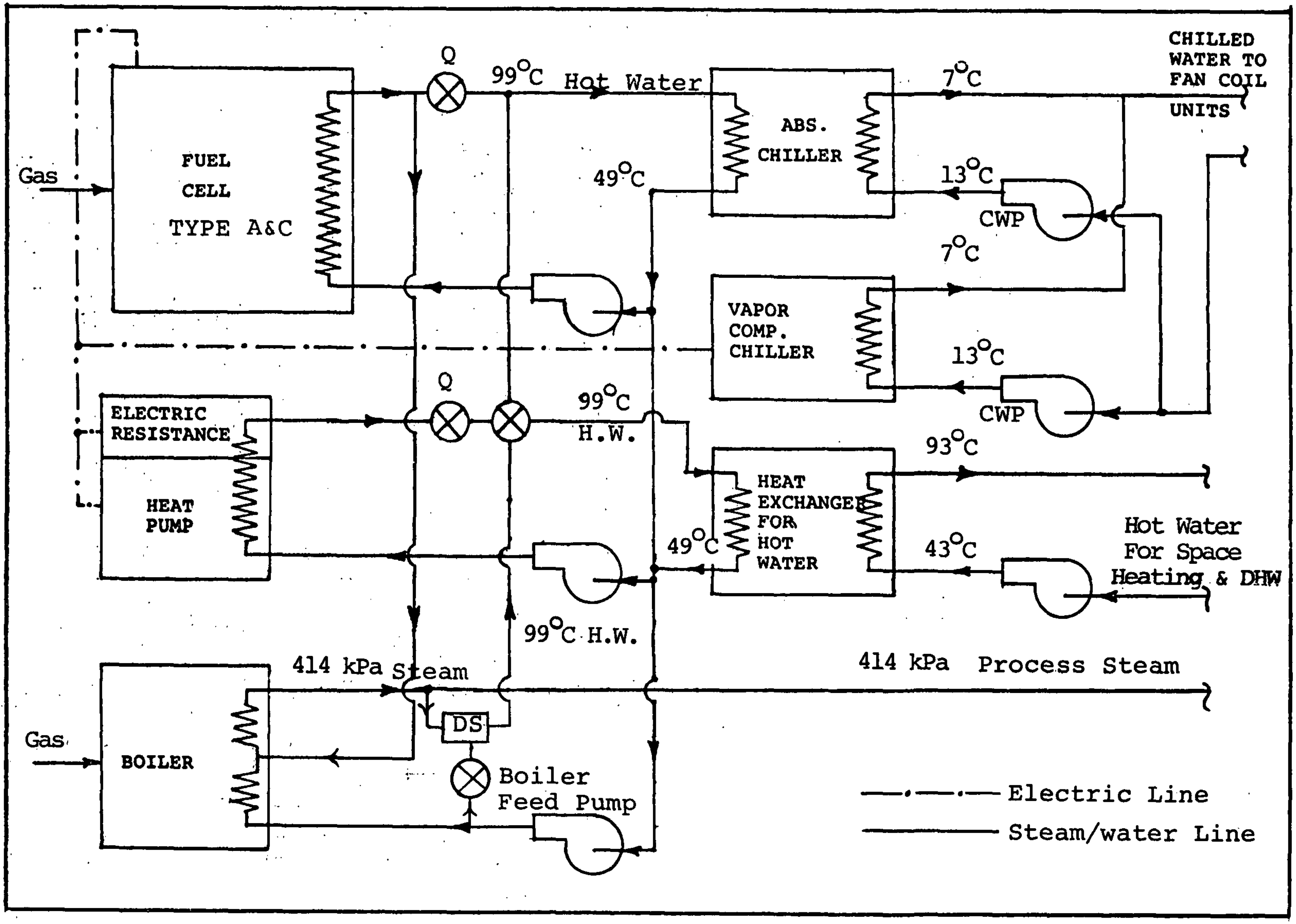


Figure 4-16. Hospital OS/IES Primary System Fuel Cell Types A and C (see Table I-3 for Equipment Sizes)

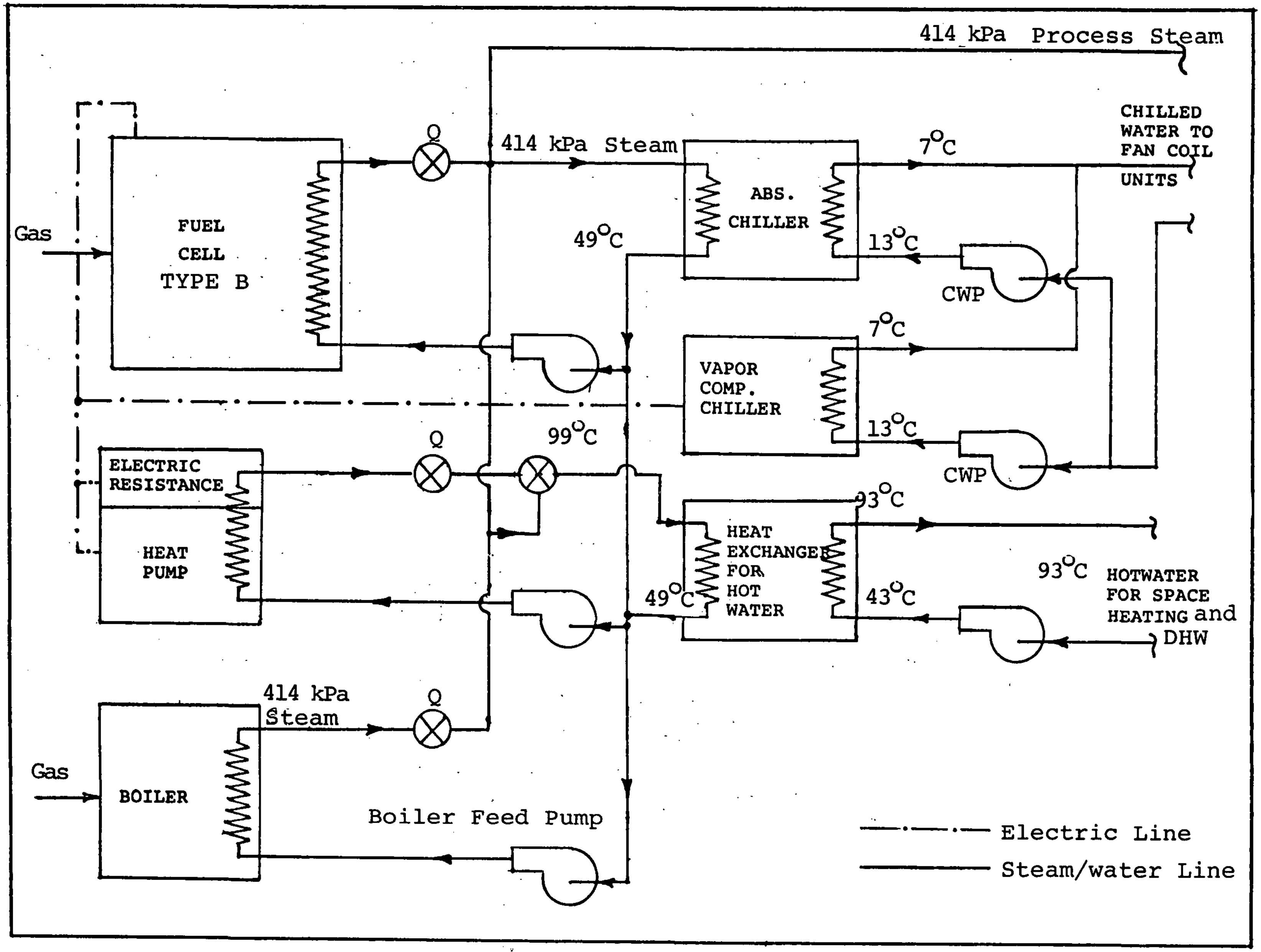
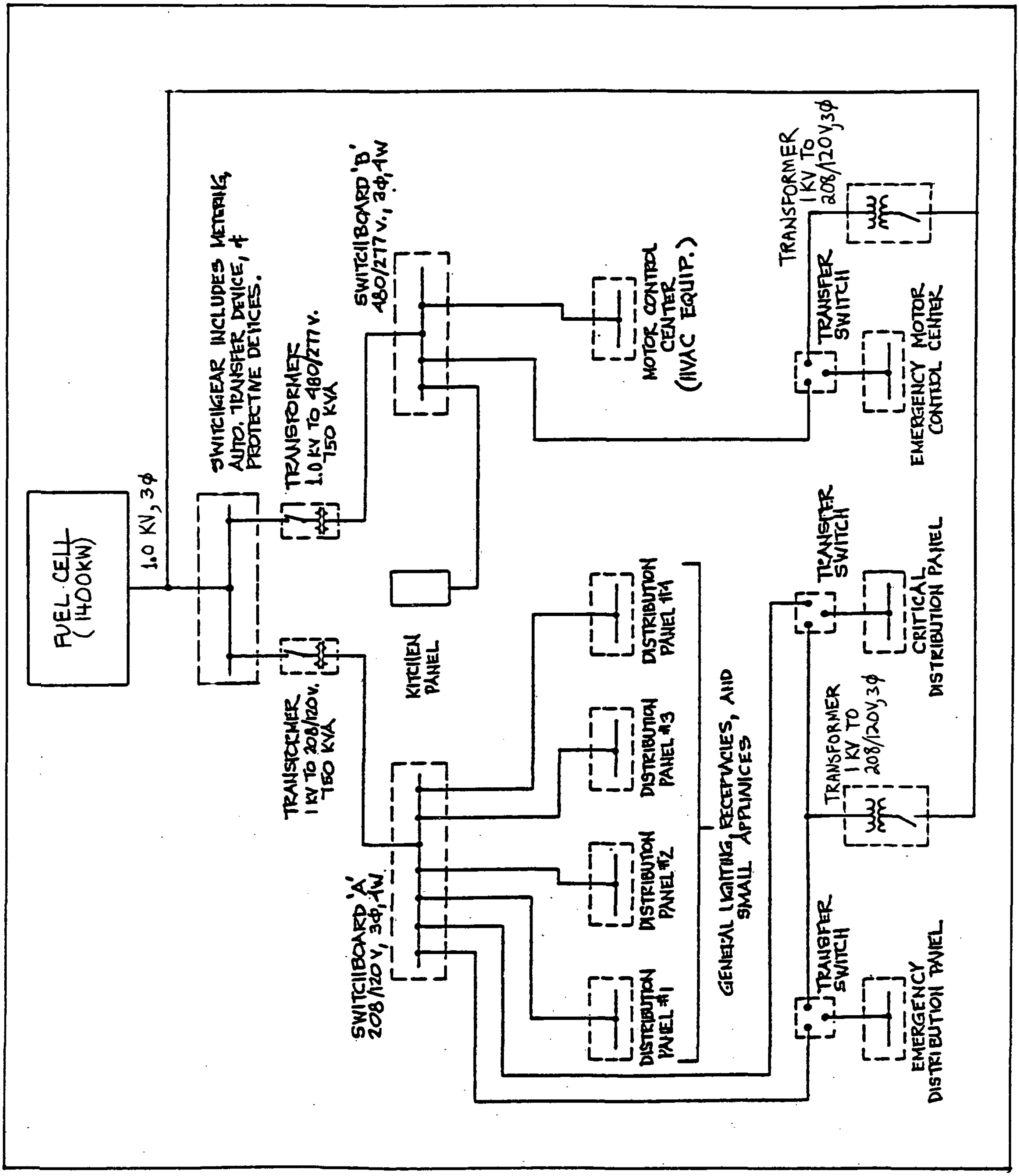


Figure 4-17. Hospital OS/IES Primary System Fuel Cell Type B (see Table I-3 for Equipment Sizes)


FUEL CELL (1400KW)
1.0 KV, 3φ
SWITCHGEAR INCLUDES METERING, AUTO. TRANSFER DEVICE, & PROTECTIVE DEVICES.
TRANSFORMER 1.0 KV TO 480/277 V. 750 KVA
TRANSFORMER 1 KV TO 208/120V. 750 KVA
KITCHEN PANEL
SWITCHBOARD 'B' 480/277 V., 3φ, 4W
MOTOR CONTROL CENTER (HVAC EQUIP.)
TRANSFORMER 1 KV TO 208/120V,3φ
TRANSFER SWITCH
EMERGENCY MOTOR CONTROL CENTER
SWITCHBOARD 'A' 208/120 V, 3φ, 4W
DISTRIBUTION PANEL #1
DISTRIBUTION PANEL #2
DISTRIBUTION PANEL #3
DISTRIBUTION PANEL #4
GENERAL LIGHTING, RECEPTACLES, AND SMALL APPLIANCES
TRANSFER SWITCH
CRITICAL DISTRIBUTION PANEL
TRANSFORMER 1 KV TO 208/120V,3φ
TRANSFER SWITCH
EMERGENCY DISTRIBUTION PANEL

CHAPTER 5

ECONOMIC EVALUATION

In order to compare the costs of each on-site fuel cell system with those of conventional systems an economic evaluation of the five alternative systems for each building/location combination was performed. Because the fuel cell systems are generally more capital intensive than conventional systems while conventional systems generally have higher annual energy costs (for fuel and electricity), the systems were compared on the basis of their life cycle economics. The methodology that was used for these comparisons is discussed in Section 5.1. Economic data assumptions and cost data are discussed in Sections 5.2 and 5.3, respectively.

5.1 Methodology

All life cycle cost comparisons were based on a calculated, levelized annual cost, which is defined as "the minimum constant net revenue required each year of the life of the project to cover all expenses, the cost of money, and the recovery of the initial investment [1]". In general,

$$\text{levelized annual cost} = \text{levelized fixed charges} + \text{levelized operating costs} - \text{levelized revenues} \quad (5\text{-}1)$$

However, for this comparative study, levelized revenues were zero, except for one case where we consider power sales to the utility, which is discussed in Chapter 7. Thus, even if some sort of revenues resulted from the provision of this service, that revenue would be identical for each of the five alternative systems considered.

A deterministic methodology, specified by NASA Lewis Research Center and similar to that developed by Phung [2] was used for this purpose. Some of the features of this methodology include:

- both inflation and cost escalation are explicitly and separately accounted for (however, inflation was assumed to be zero).

- income taxes are accounted for, and investment tax credit (if any) is treated as a reduction in first year taxes

- cost increases during construction are modelled

- all salvage or residual values are assumed to be zero

Other assumptions made for the economic analysis include the following:

- the investment is made at the start of the system's service life

- the investing organization can be treated as a limitless pool of money with unchanging debt to equity ratio

- cost of debt, cost of equity, and all tax rates are constant throughout the service life

- the effect of retirement dispersion is assumed negligible

- flow-through accounting is assumed throughout

- all levelized costs are expressed in reference-year (1978) dollars

In calculating numerical values levelized annual cost, as defined by Equation 5-1, levelized fixed charges, LFC, were computed as

$$LFC = C \cdot FCR \qquad (5\text{-}2)$$

where FCR = fixed charge rate, as defined in Appendix J
C = capital investment in 1978 dollars.

All other costs and revenues that occur over the life of the system were levelized, based on the equation

$$LC = (CRF_{m,n}) \cdot (PV) \qquad (5\text{-}3)$$

where $LC =$ levelized annual operating cost in 1978 dollars

$PV = \sum_{j=1}^{n} P_j/(1+m)^j$

P_j = expenditure (or revenue) in year j

$CRF_{m,n}$ = capital recovery factor, as defined in Appendix J

m = after-tax cost of capital

n = economic life of the investment

A more complete mathematical description of the life cycle cost methodology is provided in Appendix J.

5.2 Economic and Financial Data

Regardless of the methodology used, the rigorous calculation of system life cycle cost requires the specification of a large number of economic and financial variables and parameters, including

- inflation rate
- type of ownership
- cost of debt and equity
- debt to equity ratio
- depreciation method
- applicable federal, state, and local tax rates
- applicability of investment tax credit
- system economics and tax lives
- construction time
- insurance costs
- various cost escalation rates

With the exception of inflation and escalation rates, these data values tend to vary from one application to another. Inflation was assumed equal to zero in all cases, in order to simplify interpretation of the economic results produced. While it is recognized that inflation will be a significant economic factor over the next several years, its value is not likely to affect the relative economics of conventional versus the on-site, integrated energy systems. The specification of appropriate values for cost of debt, cost of equity, and all cost escalation rates are consistent with an assumed zero inflation rate. A further assumption was that the working capital include in this analysis is determined based on the total building costs rather than the specific energy system employed and that variations in working capital for buildings differing only in their energy systems would be negligible. Finally, no investment tax credit was taken for either the conventional system or the fuel cell systems since tax credits on heating and cooling equipment are not generally available to private building owners [3].

The above and other economic assumptions are documented in Table 5-1. Debt and equity costs and insurance and tax rates were based on:

- personal communication with a Washington area real estate developer [4] for the apartment building and retail store
- personal communication with a Pennsylvania hospital administrator [5] for the hospital.

The ratio of preferred equity to total capital was assumed to be zero, since a preferred equity arrangement is generally not used in real estate investment and almost never used by private land developers [4].

5.3 Cost Estimates

Calculation of levelized annual costs required consistent estimates of the capital, operating and maintenance, and energy costs of each conventional and fuel cell energy system. These estimates and supporting cost data are described below for each class of costs.

TABLE 5-1

DATA VALUES AND ASSUMPTIONS FOR ECONOMIC ANALYSIS

ECONOMIC DATA ITEM	BUILDING		
	LOW-RISE APARTMENT	RETAIL STORE	HOSPITAL
ASSUMED OWNERSHIP	DIRECT OWNERSHIP TENANCY IN COMMON	LIMITED PARTNERSHIP	NON-PROFIT CORPORATION
Economic Life, years	25	25	25
Tax Life, years	25	25	25
Building design and Construction Time	3.0	3.5	4.0
Composition Federal and State Income Tax Rate	.42	.45	0
Insurance and Local Taxes	.035	.035	.035
Ratio of Debt Capital to Total Capital	.80	.75	.45
Cost of Debt With Inflation Without Inflation	 .125 .042	 .120 .027	 .097 .013
Ratio of Common Equity to Total	.20	.25	.55
Cost of Common Equity With Inflation Without Inflation	.100 .019	.110 .028	.10 .019
Depreciation Method	Straight Line	Straight Line	Straight Line
Investment Tax Credit	0	0	0

5.3.1 Capital Costs

Capital cost estimates were developed to identify the differential costs for providing equivalent service using conventional and fuel cell systems. Estimates are intended to have a level of accuracy of 20% plus or minus.

Conventional Systems

For each application, boundaries were established to determine those portions of the total building for which capital costs would be developed. Essentially, only those portions that change with the use of all-electric, gas-electric, or fuel cell system were estimated. Costs were based on three sources, as appropriate:

- Means Building Construction Cost Data, 1978, National Average Costs [6]
- Quotations from manufacturers or distributors of equipment
- Ballinger Company in-house estimation of distribution systems and other elements that could not be readily estimated using the above sources.

Conventional system cost estimates were based on the system designs described in Chapter 4 of this report.

Table 5-2 summarizes estimated capital costs for the conventional systems as well as the fuel cell systems. Capital cost estimates for each application, location, and system type are presented as follows:

APPLICATION	TABLE NUMBER
Residential	5-3
Retail Store	5-4
Hospital	5-5

TABLE 5-2

CAPITAL COST SUMMARY

- ITEMS INCLUDED, AS APPLICABLE

  HVAC Equipment, Central Plant
  HVAC Equipment, Secondary
  FUEL CELLS, Installed
  MECH/ELECT Equipment Space
  Electrical Service Equipment, Panels
  Emergency Power
  Domestic Water Heater

- CAPITAL COSTS (National Average Unit Costs, 1978$)

Application	Location	System Type				
		All Elect	Gas Elect	Fuel Cell A	Fuel Cell B	Fuel Cell C
Residential	Washington	42,960	41,160	162,196	152,451	149,181
	Chicago	42,960	41,160	157,756	148,086	145,021
	Dallas	42,960	41,160	158,536	148,876	145,656
Retail Store	Washington	208,075	137,565	545,994	463,704	437,426
	Chicago	287,995	156,415	540,880	457,511	435,226
	Dallas	208,075	140,765	547,008	466,204	443,793
Hospital	Washington	409,995	250,670	926,805	783,883	719,728
	Chicago	379,455	237,870	851,833	777,043	670,049
	Dallas	414,455	250,670	946,065	759,855	711,692

TABLE 5-3

ESTIMATED CAPITAL COSTS OF CONVENTIONAL ENERGY SYSTEMS:

LOW-RISE APARTMENT BUILDING (1978$)

● No Significant Difference between Locations

ITEM	COST	
	ALL-ELECTRIC	GAS-ELECTRIC
Electrical Service	3120	3120
Electrical Panels	9600	7320
HVAC Equipment		
Heat Pump/Resist. Htr.	26880	----
Gas Furnace w/split System DX Cooling	-----	26880
Domestic Water Heaters	3360	3840
Total	42960	41160

Notes 1) Other Equipment Unchanged

2) Each Dwelling Unit Has Its Own Independent Heating and Cooling Plant

3) Cost of Heat Pump vs Gas/DX Unit Determined by Market Competition

TABLE 5-4

ESTIMATED CAPITAL COSTS OF CONVENTIONAL ENERGY SYSTEMS:

RETAIL STORE

Item	COST (1978 $)					
	ALL-ELECTRIC			GAS-ELECTRIC		
	Washington	Chicago	Dallas	Washington	Chicago	Dallas
Electrical Service	23,400	23,400	23,400	19,290	19,290	19,290
HVAC Equipment						
Vapor Compression Chiller	---	---	---	49,600	68,450	52,800
Gas-Fired Boiler	---	---	---	4,400	4,400	4,400
Air-Air Heat Pumps, w/Suppl. Resistance Heating	198,000	277,920	198,000	---	---	---
Air Handling Units	Included With Heat Pumps			55,000	55,000	55,000
Domestic Water Heater	8,200	8,200	8,200	1,300	1,300	1,300
Emergency Power	8,475	8,475	8,475	7,975	7,975	7,975
Mech/Elect Equipment Space*	(30,000)	(30,000)	(30,000)	---	---	---
TOTAL	208,075	287,995	208,075	137,565	156,415	140,765

* All-Electric system is given a credit for its reduced space requirements relative to the Gas-Electric system.

TABLE 5-5

ESTIMATED CAPITAL COSTS OF CONVENTIONAL ENERGY SYSTEMS:

HOSPITAL

Item	COST (1978 $)					
	ALL-ELECTRIC			GAS-ELECTRIC		
	Washington	Chicago	Dallas	Washington	Chicago	Dallas
Electrical Service Entrance	22,760	22,760	22,760	13,700	13,700	13,700
Electrical Panels	14,565	14,565	14,565	4,340	4,340	4,340
HVAC Equipment						
Absorption Chiller	---	---	---	80,000	67,200	80,000
Gas-Fired Steam Boiler	---	---	---	56,200	56,200	56,200
Water-Air Heat Pumps	290,000	260,000	295,000	---	---	---
Air Handling Units	Included With Heat Pumps			40,000	40,000	40,000
Domestic Water Heaters	26,200	26,200	26,200	5,500	5,500	5,500
Emergency Power	55,930	55,930	55,930	50,930	50,930	50,930
Total	409,455	379,455	414,455	250,670	237,870	250,670

Fuel Cell Systems

Estimates are based on the fuel cell systems without utility tie-in, described in Chapter 4 of this report. Capital costs for fuel cell systems involved four elements:

- Fuel cell modules, as supplied to the installing contractor
- Installation of fuel cell modules
- Other energy conversion and distribution equipment, installed
- Additional space, support, and protection required for the conventional components of the fuel cell systems.

Costs of the fuel cell modules, delivered to the job site, were developed based on the following equation specified by NASA:

$$C = C_o (kW)^{0.93} \qquad (5\text{-}4)$$

where C = fuel cell module purchase price, 1978 dollars

kW = fuel cell module size, kilowatts

$$C_o = \begin{cases} 615 \text{ \$/kW, for a Type A fuel cell} \\ 463 \text{ \$/kW, for a Type B fuel cell} \\ 420 \text{ \$/kW, for a Type C fuel cell} \end{cases}$$

Installation costs for fuel cell modules are based on the following assumptions:

- Fuel cell module equipment cost includes delivery to the job site by truck, installation instructions (including shop drawings if required), and start-up assistance by manufacturer's representative.
- The installation contractor is required to provide a supporting base, attachment to that base, and connections for natural gas, electric power output, thermal energy output, and thermal energy return.

- The fuel cell modules are suitably constructured for exterior installation. Governing regulations require physical protection (chain-link fence) and visual screening (landscaping).
- The installation contractor is required to start up and "check out" the system.
- The installation contractor is familiar with fuel cell systems, they are treated as "conventional" systems.

Capital cost estimatef for the fuel cell systems in this study are based on exterior installation. Interior installation would result in increased costs varying over a substantial range. For example, a simple shell enclosure would cost about \$55-\$90/kW (or \$15.00/sq. ft. of shelter), while an enclosure to match good quality building: \$100-\$180/kW (or \$30.00/sq. ft. of shelter).

Installation costs were estimated as follows. Detailed installation cost estimates were first prepared for nine sample fuel cell arrays with total installed capacities of 100, 500, and 1,000 kW, each comprised of either 2, 4, or 10 modules. The results of these estimates are presented in Table 5-6. It was then assumed that the ratio of installation cost to installed capital cost was constant for fuel cell systems in each of the following size ranges:

Size Range	Fuel Cell System Capacities Included	Represented by System With Capacity Of
A	0 to 200kW	100
B	200 to 700kW	500
C	700kW and greater	1,000

For a given fuel cell array contained in size range A, for example, and comprised of "n" identical modules, the ratio of installation cost to installed capital cost was defined as R_{An}, and the values R_{A2}, R_{A4}, and R_{A10} were taken from Table 5-6, for n = 2, 4, or 10, respectively. Values of R_{An} for other values of n were then calculated by interpolation or extrapolation as follows:

TABLE 5-6

INSTALLATION COSTS FOR TYPICAL FUEL CELL ARRAYS (1978 $)

		COST BY WORK ITEM (1978 $)								
	Total Capacity:	100 kW			500 kW			1000 kW		
	Number of Modules:	10	4	2	10	4	2	10	4	2
WORK ITEM	• Provide Concrete Slab	1772	1177	1188	3975	2991	2920	6377	5495	5090
	• Unload Bolt in Place	9000	6800	6000	30000	17600	12000	40000	24000	10800
	• Connect Gas Service	500	240	150	750	500	420	1200	840	680
	• Connect Thermal Service	1000	400	200	1000	460	300	1110	600	400
	• Connect Power	2800	2800	2800	14000	14000	14000	28000	28000	28000
	• Provide Chain Link Fence	776	726	658	1103	1118	2920	1401	5495	5090
	• Provide Landscaping	370	350	315	530	535	1400	670	2635	2440
	• Check Out	2325	1165	1165	2325	1165	1165	2325	1165	1165
	Total Cost, $	18543	13658	12476	53683	38369	35125	81083	68230	53665
	Total Cost, $/kW	185	137	125	107	76.7	70.3	81.3	68.2	53.7

Number of Modules, n	R_{An} Calculated by
$2 \leq n < 4$	• interpolation between R_{A2} and R_{A4}
$4 \leq n < 10$	• interpolation between R_{A4} and R_{A10}
$n \geq 10$	• extrapolation based on R_{A4} and R_{A10}

Values of R_{Bn} and R_{Cn} were calculated similarly for size ranges B and C, respectively.

A land value for the area occupied by the fuel cell array is not included. For suburban sites and residential and hospital applications, it is unlikely that land coverage would be a factor. For a suburban retail store, however, or for any urban site, the additional coverage required for a fuel cell array might well involve a measurable cost premium.

Additional enclosed space also may be required for energy conversion and distribution equipment. For the applications studied, requirements were:

Residential:	addition of a mechanical room where none existed for conventional systems
Retail Store:	enlargement of mechanical room
Hospital:	no additional space needed.

Figure 5-1 illustrates the maximum impact condition, the addition of a mechanical equipment room for the residential application.

Table 5-2 summarizes estimated capital costs for both fuel cell and conventional systems. Capital costs for fuel cell systems, more fully broken down, are presented as follows:

Application	Location	Table Number
Residential	Washington, D.C.	5-7
Residential	Chicago	5-8
Residential	Dallas	5-9
Retail Store	Washington, D.C.	5-10

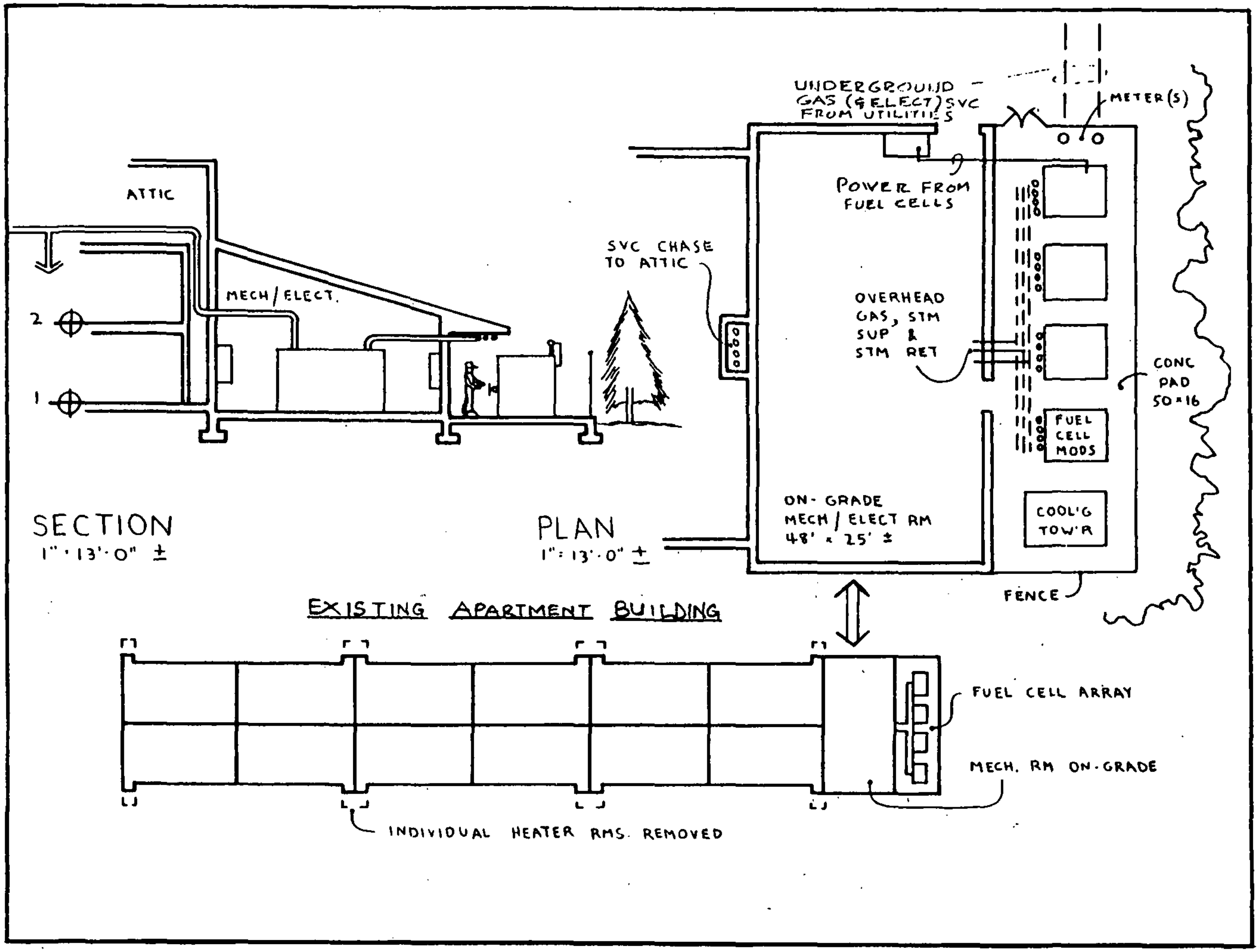


Figure 5-1. Space Impace - Low-Rise Apartment Building

TABLE 5-7

TOTAL INSTALLED CAPITAL COSTS:

LOW-RISE APARTMENT BUILDING, WASHINTON, D.C. (1978$)

Cost Item	Conventional All Elect	Conventional Gas Elect	Fuel Cell System Type A	Fuel Cell System Type B	Fuel Cell System Type C
Electrical Service Entrance	3,120	3,120	3,120	3,120	3,120
Electrical Panels	9,600	7,320	10,785	10,785	10,785
HVAC Equipment, Central Plant					
Vapor Compression Chiller			5,890	5,890	5,890
Absorption Chiller			19,800	19,800	19,800
Heat Pump			7,500	7,500	7,500
Electrical Resistance Heat			1,000	1,000	1,000
Gas-Fired Boiler			2,300	2,125	1,635
Subtotal	x	x	36,490	36,315	35,852
HVAC Equipment, Secondary	26,880	26,880	13,560	13,560	13,560
Domestic Water Heater	3,360	3,840	3,150	3,150	3,150
Emergency Power System	x	x	x	x	x
Mechanical Equipment Space	x	x	10,600	10,600	10,600
Fuel Cell Modules	x	x	53,901	44,331	41,551
Distribution Piping	x	x	23,550	23,550	23,550
Cooling Tower	x	x	7,040	7,040	7,040
Total	42,960	41,160	162,196	152,451	149,181

x Not applicable this system
o No cost change between systems for this application/location

TABLE 5-8

TOTAL INSTALLED CAPITAL COSTS:

LOW-RISE APARTMENT BUILDING, CHICAGO, ILLINOIS (1978$)

Cost Item	Conventional All Elect	Conventional Gas Elect	Fuel Cell System Type A	Fuel Cell System Type B	Fuel Cell System Type C
Electrical Service Entrance	3,120	3,120	3,120	3,120	3,120
Electrical Panels	9,600	7,320	10,785	10,785	10,785
HVAC Equipment, Central Plant					
Vapor Compression Chiller			5,890	5,890	5,890
Absorption Chiller			16,500	16,500	16,500
Heat Pump			7,500	7,500	7,500
Electrical Resistance Heat			1,000	1,000	1,000
Gas-Fired Boiler			1,860	1,760	1,475
Subtotal	x	x	32,750	32,650	32,365
HVAC Equipment, Secondary	26,880	26,880	13,560	13,560	13,560
Domestic Water Heater	3,360	3,840	3,150	3,150	3,150
Emergency Power System	x	x	x	x	x
Mechanical Equipment Space	x	x	10,600	10,600	10,600
Fuel Cell Modules	x	x	53,901	44,331	41,551
Distribution Piping	x	x	23,550	23,550	23,550
Cooling Tower	x	x	6,340	6,340	6,340
Total	42,960	41,160	157,756	148,086	145,021

x Not applicable this system

o No cost change between systems for this application/location

TABLE 5-9

TOTAL INSTALLED CAPITAL COSTS:

LOW-RISE APARTMENT BUILDING DALLAS, TEXAS (1978$)

Cost Item	Conventional All Elect	Conventional Gas Elect	Fuel Cell System Type A	Fuel Cell System Type B	Fuel Cell System Type C
Electrical Service Entrance	3,120	3,120	3,120	3,120	3,120
Electrical Panels	9,600	7,320	10,785	10,785	10,785
HVAC Equipment, Central Plant					
Vapor Compression Chiller			5,890	5,890	5,890
Absorption Chiller			19,800	19,800	19,800
Heat Pump			3,750	3,750	3,750
Electrical Resistance Heat			1,000	1,000	1,000
Gas-Fired Boiler			2,390	2,300	1,860
Subtotal	x	x	32,830	32,740	32,300
HVAC Equipment, Secondary	26,880	26,880	13,560	13,560	13,560
Domestic Water Heater	3,360	3,840	3,150	3,150	3,150
Emergency Power System	x	x	x	x	x
Mechanical Equipment Space	x	x	10,600	10,600	10,600
Fuel Cell Modules	x	x	53,901	44,331	41,551
Distribution Piping	x	x	23,550	23,550	23,550
Cooling Tower	x	x	7,040	7,040	7,040
Total	42,960	41,160	158,536	148,876	145,656

x Not applicable this system
o No cost change between systems for this application/location

TABLE 5- 10

TOTAL INSTALLED CAPITAL COSTS: RETAIL STORE, WASHINGTON, D.C. (1978$)

Cost Item	Conventional All Elect	Conventional Gas Elect	Fuel Cell System Type A	Fuel Cell System Type B	Fuel Cell System Type C
Electrical Service Entrance	23,400	19,290	x	x	x
Electrical Panels	0	0	0	0	0
HVAC Equipment, Central Plant					
Vapor Compression Chiller			18,700	18,700	18,700
Absorption Chiller			33,600	33,600	33,600
Heat Pump			14,400	14,400	14,400
Electrical Resistance Heat			1,440	1,440	1,440
Gas-Fired Boiler			14,315	14,315	10,840
Subtotal		54,000	82,455	82,455	78,980
HVAC Equipment, Secondary	198,000	55,000	55,000	55,000	55,000
Domestic Water Heater	8,200	1,300	525	525	525
Emergency Power System	8,475	7,975	250	250	250
Mechanical Equipment Space	(30,000)	Base	7,500	7,500	7,500
Fuel Cell Modules	x	x	400,264	317,974	295,174
Distribution Piping	0	0	0	0	0
Total	208,075	137,565	545,994	463,704	437,429

x Not applicable this system
o No cost change between systems for this application/location

Application	Location	Table Number
Retail Store	Chicago	5-11
Retail Store	Dallas	5-12
Hospital	Washington, D.C.	5-13
Hospital	Chicago	5-14
Hospital	Dallas	5-15

The same figures summarize capital costs for conventional systems.

Differential Energy System Costs Relative to Total Building Costs

As stated above, only differential energy system costs were analyzed in detail. However, it is important to express these differential costs as they relate to the entire building. Table 5-16 compares total building capital costs for the buildings that include the more economic conventional energy system with the total capital costs of buildings which include one of three fuel cell energy systems (Type C fuel cell system in every case). It is observed that the use of fuel cell systems increases the total building cost by:

- 20 percent for the low-rise apartment building
- 12 percent for the retail store
- 5 percent for the hospital

In interpreting these results, it should be recognized that the residential building which was studied does not include a centralized energy system for either of its conventional alternatives. Therefore, the fuel cell energy system has a greater cost impact for this application than for either of the other buildings which do include centralized (conventional) energy systems. To some extent, this is a matter of scale, e.g., a larger apartment building might well have a centralized energy system.

5.3.2 Operating and Maintenance Costs

Annual operating and maintenance (O&M) costs were estimated for fuel cells and all conventinal HVAC equipment. No geographic effects, such as varying labor rates, were included in these estimates. Fuel cell O&M costs were based strictly on fuel cell electric energy production at a rate of 6 mills/kWh, as specified by NASA LeRC.

TABLE 5-11

TOTAL INSTALLED CAPITAL COSTS:

RETAIL STORE, CHICAGO, ILLINOIS (1978$)

Cost Item	Conventional All Elect	Conventional Gas Elect	Fuel Cell System Type A	Fuel Cell System Type B	Fuel Cell System Type C
Electrical Service Entrance	23,400	19,290	x	x	x
Electrical Panels	0	0	0	0	0
HVAC Equipment, Central Plant					
Vapor Compression Chiller			18,700	18,700	18,700
Absorption Chiller			33,600	33,600	33,600
Heat Pump			14,400	14,400	14,400
Electrical Resistance Heat			1,440	1,440	1,440
Gas-Fired Boiler			14,315	12,135	10,840
Subtotal	x	72,850	82,455	80,275	78,980
HVAC Equipment, Secondary	277,920	55,000	55,000	55,000	55,000
Domestic Water Heater	8,200	1,300	525	525	525
Emergency Power System	8,475	7,975	250	250	250
Mechanical Equipment Space	(30,000)	Base	7,500	7,500	7,500
Fuel Cell Modules	x	x	395,150	313,961	292,971
Distribution Piping	0	0	0	0	0
Total	287,995	156,415	540,880	457,511	435,226

x Not applicable this system
o No cost change between systems for this application/location

TABLE 5-12

TOTAL INSTALLED CAPITAL COSTS:

RETAIL STORE, DALLAS, TEXAS (1978$)

Cost Item	Conventional All Elect	Conventional Gas Elect	Fuel Cell System Type A	Fuel Cell System Type B	Fuel Cell System Type C
Electrical Service Entrance	23,400	19,290	x	x	x
Electrical Panels	0	0	0	0	0
HVAC Equipment, Central Plant					
Vapor Compression Chiller			18,700	18,700	18,700
Absorption Chiller			33,600	33,600	33,600
Heat Pump			14,400	14,400	14,400
Electrical Resistance Heat			1,440	1,440	1,440
Gas-Fired Boiler			14,315	14,315	14,315
Subtotal	x	57,200	82,455	82,455	82,455
HVAC Equipment, Secondary	198,000	55,000	55,000	55,000	55,000
Domestic Water Heater	8,200	1,300	525	525	525
Emergency Power System	8,475	8,475	250	250	250
Mechanical Equipment Space	(30,000)	Base	7,500	10,000	7,500
Fuel Cell Modules	x	x	401,278	317,974	297,063
Distribution Piping	0	0	0	0	0
Total	208,075	140,765	547,008	466,204	442,793

x Not applicable this system
o No cost change between systems for this application/location

TABLE 5-13
TOTAL INSTALLED CAPITAL COSTS:
HOSPITAL, WASHINGTON, D.C. (1978$)

Cost Item	Conventional All Elect	Conventional Gas Elect	Fuel Cell System Type A	Fuel Cell System Type B	Fuel Cell System Type C
Electrical Service Entrance	22,760	13,700	x	x	x
Electrical Panels	14,560	4,340	4,340	4,340	4,340
HVAC Equipment, Central Plant					
Vapor Compression Chiller			33,650	42,825	33,650
Absorption Chiller			42,400	40,000	42,400
Heat Pump			30,400	39,200	30,400
Electrical Resistance Heat			1,975	1,575	1,975
Gas-Fired Boiler			25,040	16,705	16,705
Subtotal	x	136,200	133,465	140,305	125,130
HVAC Equipment, Secondary	290,000	40,000	40,000	40,000	40,000
Domestic Water Heater	26,200	5,500	5,500	5,500	5,500
Emergency Power System	55,930	50,930	2,080	2,080	2,080
Mechanical Equipment Space	0	0	0	0	0
Fuel Cell Modules	x	x	741,420	591,658	542,678
Distribution Piping	0	0	0	0	0
Total	409,450	250,670	926,805	783,883	719,728

x Not applicable this system
o No cost change between systems for this application/location

TABLE 5-14

TOTAL INSTALLED CAPITAL COSTS:

HOSPITAL, CHICAGO, ILLINOIS (1978$)

Cost Item	Conventional All Elect	Conventional Gas Elect	Fuel Cell System Type A	Fuel Cell System Type B	Fuel Cell System Type C
Electrical Service Entrance	22,760	13,700	x	x	x
Electrical Panels	14,565	4,340	4,340	4,340	4,340
HVAC Equipment, Central Plant					
Vapor Compression Chiller			18,700	33,650	18,700
Absorption Chiller			45,600	42,400	45,600
Heat Pump			25,280	30,400	25,280
Electrical Resistance Heat			2,100	1,975	2,100
Gas-Fired Boiler			20,000	25,404	22,700
Subtotal	X	123,400	111,680	133,465	114,380
HVAC Equipment, Secondary	260,000	40,000	40,000	40,000	40,000
Domestic Water Heater	26,200	5,500	5,500	5,500	5,500
Emergency Power System	55,930	50,930	2,080	2,080	2,080
Mechanical Equipment Space	0	0	0	0	0
Fuel Cell Modules	x	x	688,233	591,658	503,749
Distribution Piping	0	0	0	0	0
Total	370,455	237,870	851,833	777,043	670,049

x Not applicable this system
o No cost change between systems for this application/location

TABLE 5-15

TOTAL INSTALLED CAPITAL COSTS:

HOSPITAL, DALLAS, TEXAS (1978$)

Cost Item	Conventional All Elect	Conventional Gas Elect	Fuel Cell System Type A	Fuel Cell System Type B	Fuel Cell System Type C
Electrical Service Entrance	22,760	13,700	x	x	x
Electrical Panels	14,565	4,340	4,340	4,340	4,340
HVAC Equipment, Central Plant					
Vapor Compression Chiller	42,825	33,650	42,825	33,650	33,650
Absorption Chiller			40,000	42,400	42,400
Heat Pump			39,200	30,400	32,000
Electrical Resistance Heat			1,575	1,975	1,665
Gas-Fired Boiler			25,040	22,700	16,700
Subtotal	x	136,200	148,640	131,125	126,415
HVAC Equipment, Secondary	295,000	40,000	40,000	40,000	40,000
Domestic Water Heater	26,200	5,500	5,500	5,500	5,500
Emergency Power System	55,930	50,930	2,080	2,080	2,080
Mechanical Equipment Space	0	0	0	0	0
Fuel Cell Modules	x	x	745,505	576,810	533,357
Distribution Piping	0	0	0	0	0
Total	414,455	250,670	946,065	759,855	711,692

x Not applicable this system

o No cost change between systems for this application/location

TABLE 5-16

EFFECT OF ENERGY SYSTEM DIFFERENTIAL COSTS ON TOTAL BUILDING CAPITAL COSTS

Application & Size	Location	Total Building Cost ($\$10^3$)		Differential Cost ($\$10^3$)	Percent Cost Increase Due to Use of Fuel Cell System ($\$10^3$)
		With Conventional Energy System*	With Type C Fuel Cell Energy System		
Low-Rise Apartment Building, 1,904 M^2	Washington	646	780	134	21
	Chicago		781	136	21
	Dallas		786	140	22
Retail Store, 10,420 M^2	Washington	2,535	2,835	300	12
	Chicago		2,814	279	11
	Dallas		2,837	302	12
Hospital 11,043 M^2	Washington	9,141	9,610	469	5.0
	Chicago		9,573	432	4.7
	Dallas		9,602	461	5.0

* National average building costs applied to all locations; assumes lower cost conventional energy system, typically a gas-electric system.

Conventional equipment O&M costs were based on information supplied by PenJerDel Refrigeration Company, Consohocken, Pennsylvania, a commercial industrial maintenance contractor, as cited in a recent report by Office of Technology Assessment (OTA)[7]. These prices are considered representative of contract maintenance costs in metropolitan areas.

Costs for the major equipment items, as listed in Table 5-17, are annual costs, and include -- for listed major equipment and normally associated auxiliary equipment:

- periodic inspection, cleaning, lubrication, and adjustment
- periodic replacement of seals, belts, filters, and similar parts.

5.3.3 Energy Costs

Three types of energy prices were required to complete economic analysis of fuel cell integrated energy systems, both with and without a utility tie-in. These included:

- prices for conventionally-supplied gas and electricity
- prices for the provision of standby power
- prices for the buy-back of excess OS/IES fuel cell power by the electric utility.

Prices for conventionally-supplied gas and electricity were based on DOE's "mid-term projections" of national average energy prices for 1985. These prices are summarized in Table 5-18 for both residential and commercial customers. To make these price assumptions as fair as possible to both the conventional and on-site systems, DOE's Series C projections (representing Medium Energy Supply and Demand) were used. According to DOE [8]:

> (Mid-Term) forecasts are presented for five scenarios (A, B, C, D, and E), each based on a different set of

TABLE 5-17

ANNUAL OPERATING AND MAINTENANCE COST ASSUMPTIONS

Equipment Item*	LOW-RISE APARTMENT BUILDING ENERGY SYSTEM			RETAIL STORE ENERGY SYSTEM			HOSPITAL ENERGY SYSTEM		
	All-Electric	Gas/Electric	OS/IES	All-Electric	Gas/Electric	OS/IES	All-Electric	Gas/Electric	OS/IES
Fuel Cell, \$/kWh	-	-	0.006	-	-	0.006	-	-	0.006
Heat Pump, \$/kW_t	11.4	-	11.4	11.4	-	11.4	11.4	-	11.4
Vapor Compression Chiller, \$/kW_t	-	18.8	18.8	-	6.25	6.25	-	-	6.25
Absorption Chiller, \$/kW_t	-	-	22.7	-	-	7.67	-	7.67	7.67
Boiler (or Furnace), \$/kW_t	-	3.41	3.41	-	3.41	1.70	1.70	1.02	1.36 1.70

* NOTE: Annual O&M costs for electric resistance heaters were assumed to be negligible in all cases.

TABLE 5-18

ENERGY PRICE ASSUMPTIONS FOR 1985
(Expressed in 1978 dollars per 10^6 Btu)

DATA ITEM	APPLICATION CLASS	
	RESIDENTIAL	COMMERCIAL
• Electricity Price (Annual Escalation)	12.29 0.7%	12.26 0.8%
• Gas Price (Annual Escalation)	3.47 2.1%	3.02 2.3%

> assumptions. These assumptions concern the rate of economic growth, the amount of domestic energy resources remaining to be discovered, the cost of extracting these resources, and the world oil price.....Series C assumes moderate levels for all four variables and so it is the middle, or "central," scenario.

The other sets of projections were used to help establish a reasonable range of variation for these median values and to estimate price escalation rates.

The rates for standby service that were assumed for this study included the following:

- a fixed standby service rate of 1 $/kW of backup capacity provided (1978 $)
- a monthly demand charge of 4 $/kW for any standby power purchases required (1978 $)
- an energy charge of 33 mills/kWh (1978 $)

The standby service charge was based on Pacific Gas and Electric Company's S-1 rate schedule, included as Appendix K. The demand and energy charges were calculated to be consistent with the national average energy prices assumed below.

Electric utility rates for the purchase of excee power from an OS/EIS facility would likely be based on utility average production cost at the time the excess power is made available. For most utilities, these production vary continuously over each day and the year, although the greatest variation is between on- and off-peak periods and were based on the utilities average production costs for each interval. Specifically, the assumed rates were:

- 28.7 mills/kWh, for on-peak power
- 20.1 mills/kWh, for off-peak power

These values were based on average production costs (or "running rates") for Public Service Electric and Gas Company in Newark, New Jersey, and the ratio of average on- and off-peak production costs used in a recent EPRI study of fuel cell dual energy use systems [10].

References

1. "Groundrules for Economic Analysis," prepared by NASA-Lewis Research Center, internal document prepared for Contract DEN 3-89, April 12, 1979.

2. D.L. Phung, The Discounted Cash Flow (DCF) and Riverine Requirement (RR) Methodologies in Energy Cost Analysis, Institute for Energy Analysis, Oak Ridge Associated Universities, (ORAU/IEA-78-18(R)), September 1978.

3. Oak Ridge National Laboratory, Market Assessment of Fuel Cell Total Energy Systems, Summary Report, (ORNL-CON-36), March 1979.

4. Personal Communication, Mr. William Reeves, Interstate Land Development, Incorporated.

5. Personal Communication, M.r James Woods, Administrator, New Carlisle Hospital, New Carlisle, Pennsylvania.

6. R.S. Means Company, Incorporated, Building Construction Costs Data, 1978, 37th Annual Edition, Duxbury, Massachusetts, 1978.

7. Office of Technology Assessment, Congress of the United States, Application of Solar Technology to Today's Energy Needs, Volume 1.

8. U.S. Department of Energy, Energy Information Administration, Annual Report to Congress 1978, Volume 3: Forecasts, (DOE/EIA 0173/3, Volume 3 (of 3)).

9. Edison Electric Institute, Statistical Yearbook of the Electric Utility Industry for 1977, October 1978, Number 45.

10. R.A. Wakefield, et al., Mathtech, Incorporated, An Analysis of the Application of Fuel Cells in Dual Energy Use Systems, Prepared for the Electric Power Research Institute, February 1979.

CHAPTER 6

BASE CASE RESULTS AND DISCUSSION

This chapter presents the study results for on-site fuel cell systems that maintain no type of utility tie-in. These include life cycle costs and annual energy consumptions for the three fuel cell systems and the two conventional systems. First, Section 6.1 presents the base case results, which are the product of the methodology described in Chapter 4 and the assumptions and inputs discussed in Chapter 5. Then, in Section 6.2, the effects of making various alternative assumptions are evaluated. Included are assessments of the effects of varying electricity prices, gas prices, fuel cell costs, tax credits, and ownership assumptions, and utilizing thermal storage. Economic and energy results for the cases where utility tie-in is assumed are discussed in Chapter 7.

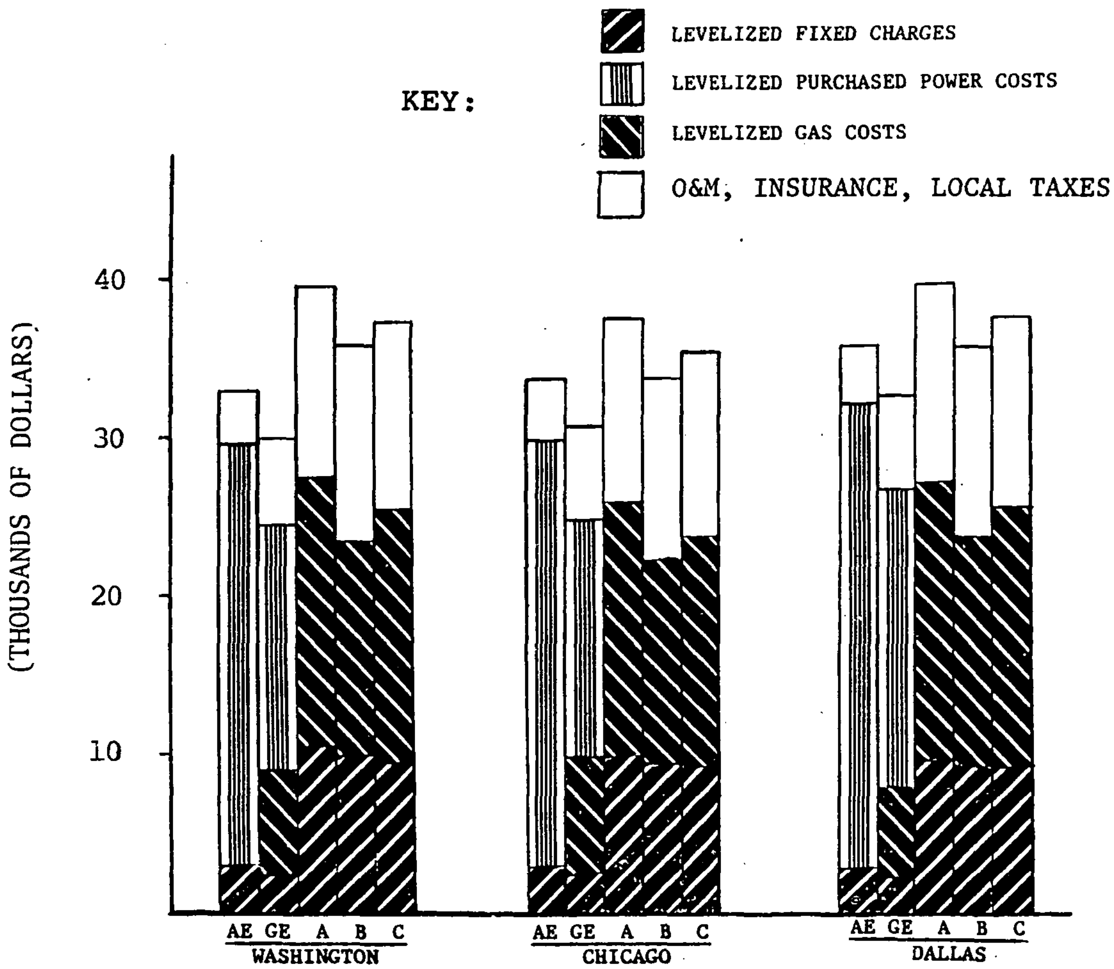
6.1 Base Case Results

6.1.1 Levelized Annual Costs

The economic results for the three buildings are presented below by application. In each case, levelized annual costs for the five energy systems are displayed graphically for each location and across locations. These same results are numerically tabulated in Appendix L.

Residential

Levelized annual costs for the apartment building are presented in Figure 6-1. In general, fuel cell system life cycle costs are higher than those for conventional systems, except that the Type B system is roughly even with the all-electric system in both Chicago and Dallas. The gas/electric system offers the lowest life cycle costs in all cases, due to its low capital cost relative to fuel cell systems and its



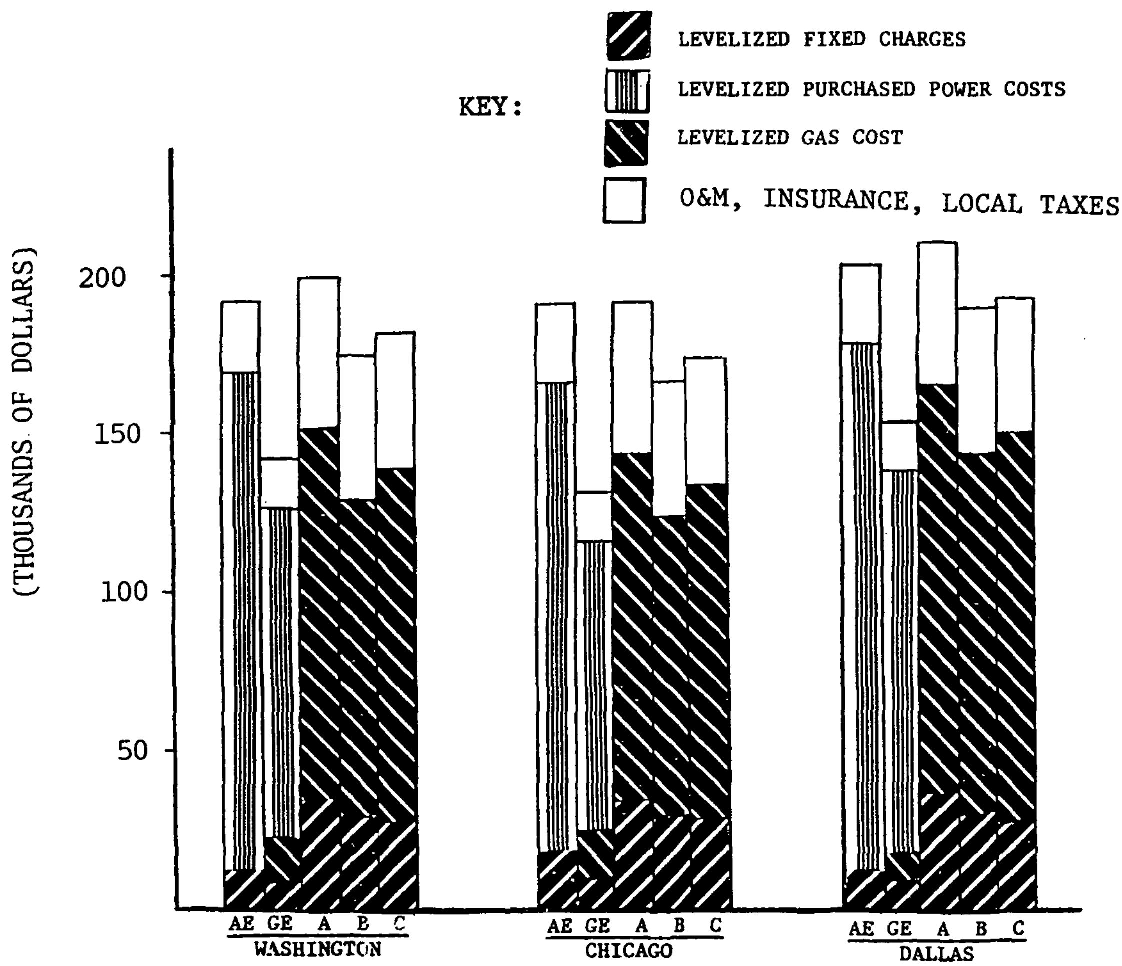
SYMBOLS: AE = All-Electric System
GE = Gas/Electric System
A = OS/IES With Type A Fuel Cell
B = OS/IES With Type B Fuel Cell
C = OS/IES With Type C Fuel Cell

FIGURE 6-1. Levelized Annual Cost: Residence low energy cost relative to the all electric system. The principal contributors to the fuel cell systems' higher costs are clear once these costs are broken down. Specifically, fuel cell system fixed costs and O&M costs both are two to four times those of conventional systems, while fuel cell system energy costs are only lower by 25 to 55 percent. Since, in this case, fixed costs and O&M make up 35 to 45 percent of the total integrated energy system life cycle costs, the cost savings do not offset cost increases. The reasons for the fuel cell systems' higher fixed and O&M costs are that these systems are centralized in terms of their physical configuration, and are being compared with unitary, conventional energy systems, comprised of standard, low-cost heating and cooling equipment located in each apartment unit. Unitary conventional systems are, quite obviously, the more economical choice for an apartment building of this size.

Two other observations can be made from these results. First, the more efficient advanced technology (Type B) fuel cell system is the most economic due to its low energy costs, while the Type A fuel cell system is least attractive due to its lower efficiency with a 150° F return temperature. Second, changes in building site do cause some changes in the magnitudes of the five energy systems costs but do not offset any of the conclusions drawn above.

Retail Store

Levelized annual costs for the retail store are presented in Figure 6-2. Except for the Type A fuel cell system, OS/IES costs for the store are lower for the all electric system. However, costs for all three fuel cell systems are still higher than those for the gas electric system. The chief cause of the fuel cell system's increased attractiveness relative to the all electric system is that the latter system's fixed and O&M costs have increased relative to those of the



SYMBOLS: As Defined in Figure 6-1.

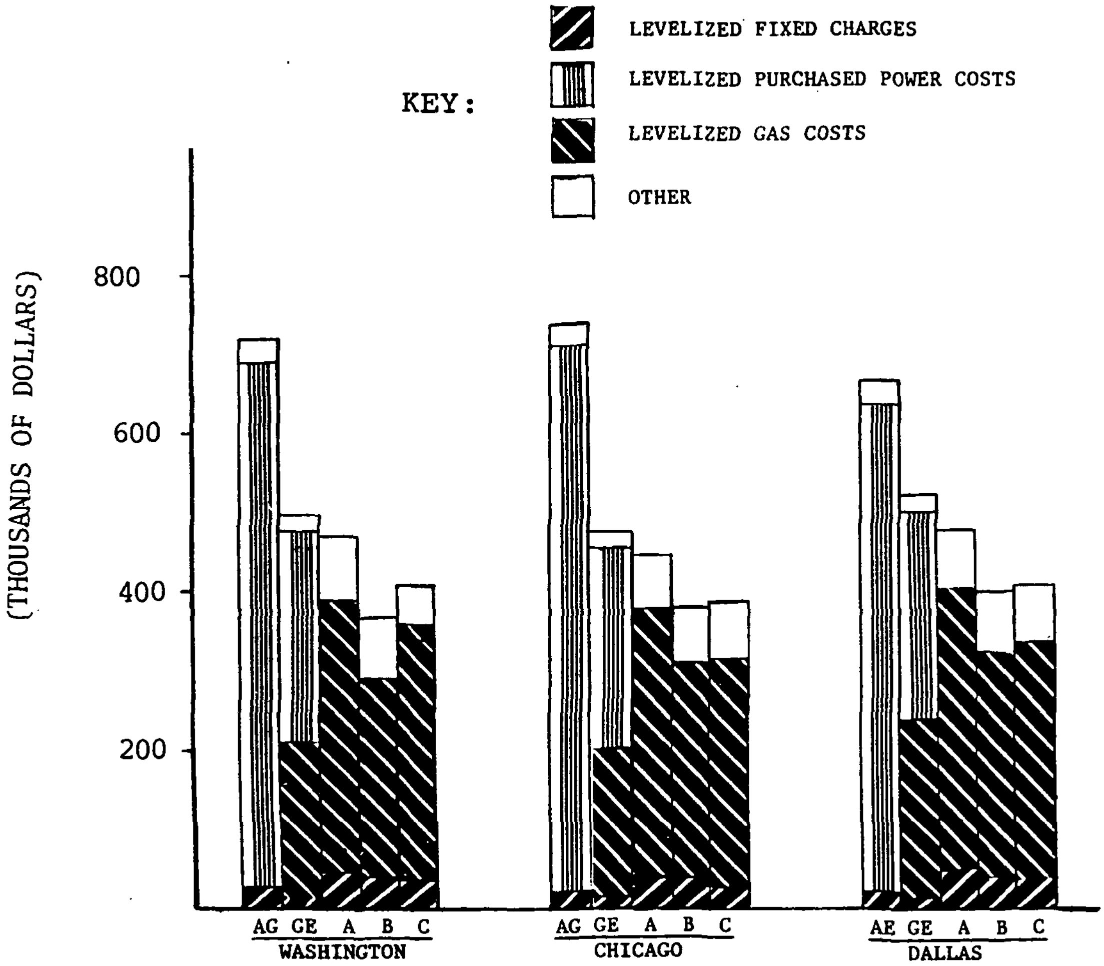
FIGURE 6-2. Levelized Annual Cost: Retail Store fuel cell systems. Once again, the low capital and O&M costs of the gas electric system keep its costs well below those of the fuel cell systems. The economic relationship between the three fuel cell systems remains approximately the same as for the apartment building.

The geographic sensitivity of the retail store life cycle costs is relatively small, but an interesting observation can be made, based on Figure 6-2. In particular, it is observed that fuel cell system life cycle costs increase by a greater percentage than do all-electric system costs when shifting from Chicago to Dallas. This is a direct result of the substitution of space cooling load, which is met quite economically by the all electric system, for space heating load, which is more economically supplied by the fuel cell systems.

Hospital

A most notable aspect of the hospital results presented in Figure 6-3 is that all of the on-site fuel cell systems had a lower levelized annual cost than either conventional system. The primary reason for this result is the dramatic increase in the relative importance of energy costs as a component of overall life cycle costs. Specifically, for the hospital, energy costs account for 74 percent of Type C fuel cell system life cycle costs and 93 percent of the gas electric system life cycle costs. For the retail store, on the other hand, corresponding percentages are 61 percent and 84 percent, respectively. Both ratios are even smaller for the residential application.

It is interesting to note, in this case, that the ratios of the fuel cell systems' to conventional systems' fixed costs and operating costs still remain high. Thus, it is the high thermal and electric load factors of the hospital that increase the relative importance of the energy cost component and make hospitals a prime application for fuel cells.



SYMBOLS: As Defined in Figure 6-1.

FIGURE 6-3. Levelized Annual Cost: Hospital

6.1.2 Annual Energy Consumptions

Annual energy consumption results for the three buildings are presented below by application. In each case, the total amounts of energy consumed annually for the five energy systems are displayed graphically for each location and across locations. These same results are numerically tabulated in Appendix L.

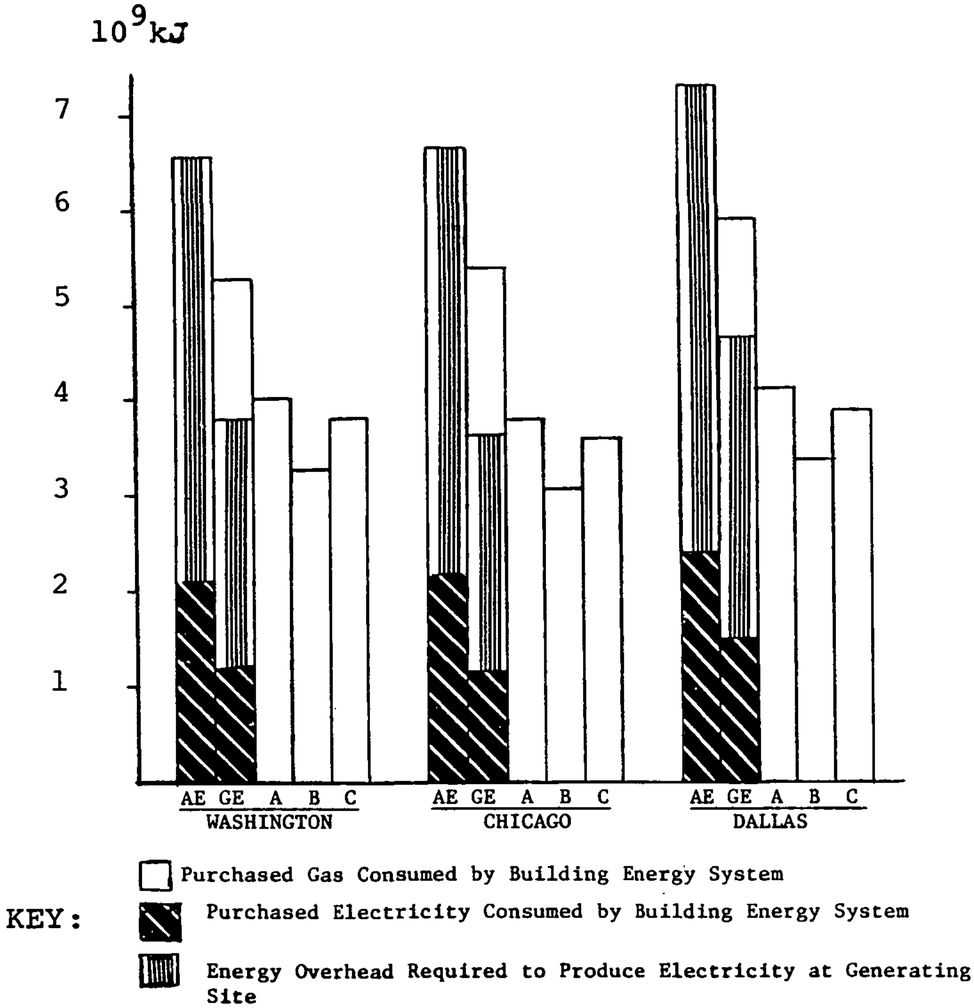
Residential

The fuel cell system annual energy consumptions shown in Figure 6-4 are significantly lower than those of the conventional systems when the inefficiency of central station power conversion is taken into account. Of course, this ranking reverses if one considers only the amount of energy consumed at the building site. Such a comparison (of on-site consumption) is fair only if a unit of electric energy is approximately equivalent to a unit of heat from the combustion of gas. This is rarely the case. If, on the other hand, the electricity is generated using energy resources such as coal or nuclear, which are less scarce (than gas), it may also be unfair to base comparisons strictly on total resources consumed. We have not attempted to resolve this dilemma here. Instead, building energy results are presented in such a way that it is clear what fraction of total energy resource consumption takes place on-site and what fraction takes place at a central station power plant. The reader may then draw his own conclusions about the relative values of energy consumed by conventional and fuel cell systems.

The effects of geographic location on apartment building energy consumption are minor. However, on-site fuel cell systems tend to require the least energy in climates where heating requirements predominate, while the resource requirements of conventional systems are slightly lower where there is a mixture of heating and cooling, as in Washington, D.C.

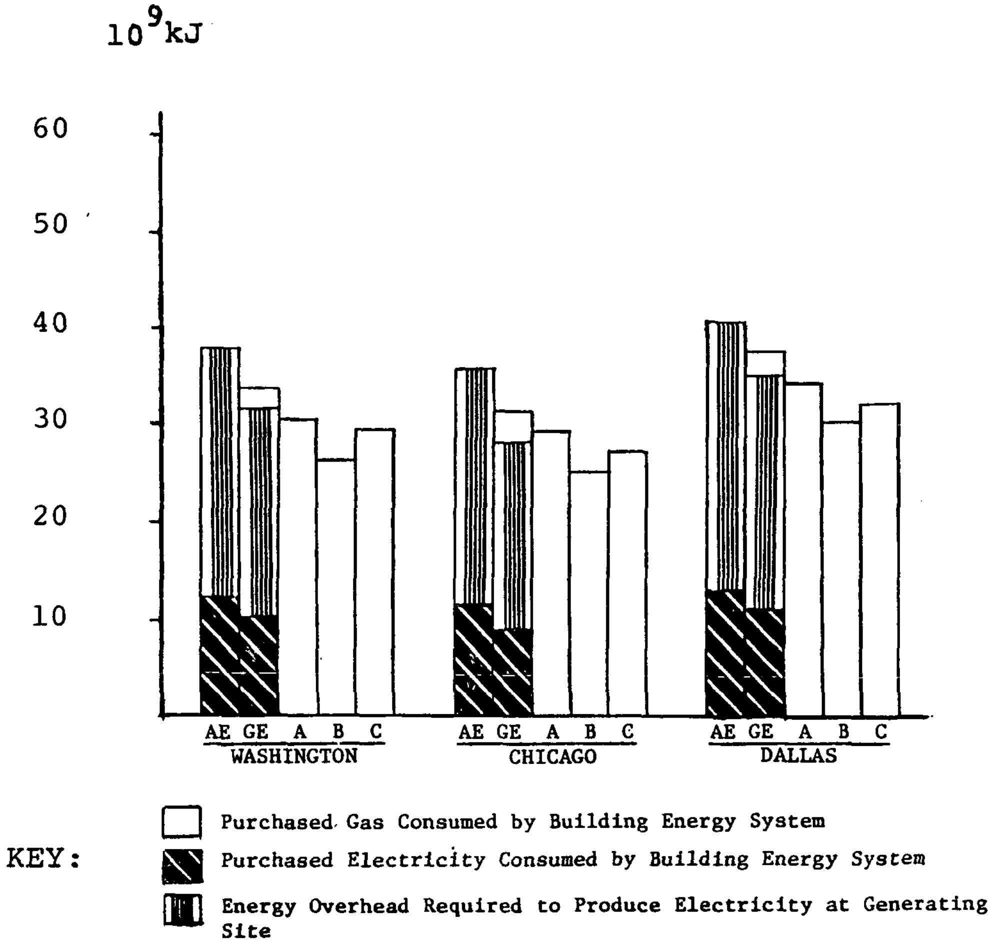
Retail Store

As Figure 6-5 shows, the energy resource savings of the fuel cell systems relative to the conventional systems are much smaller for the store than for the residential application. There are two reasons for this:



SYMBOLS: As Defined in Figure 6-1.

FIGURE 6-4. Annual Energy Consumption: Residence



SYMBOLS: As Defined in Figure 6-1.

FIGURE 6-5. Annual Energy Consumption: Retail Store

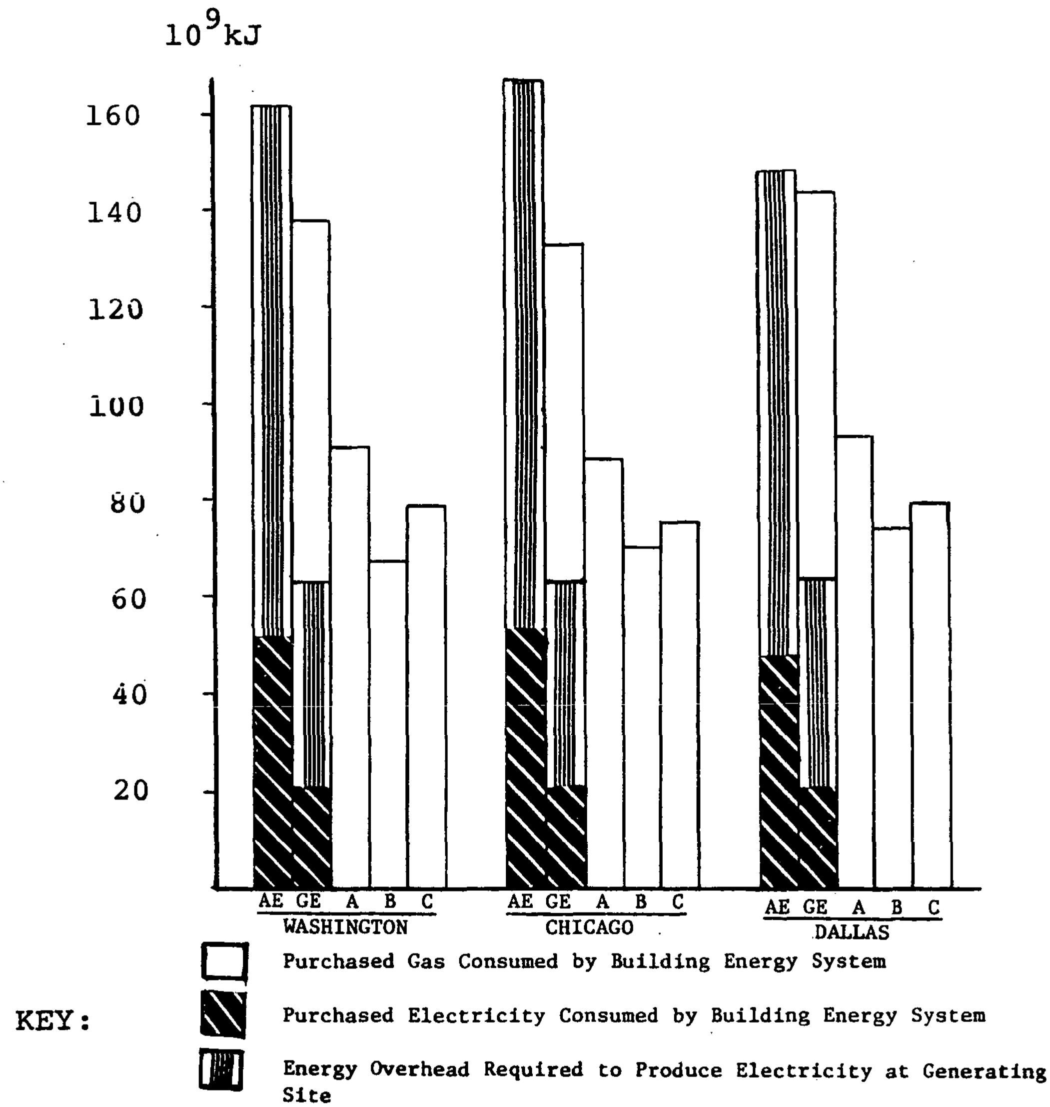
- A much larger fraction of the store's annual energy needs are for space cooling and this is a requirement that the conventional systems can satisfy very efficiently; and
- The larger, more centralized, conventional energy equipment used for the retail store is, itself, more efficient than the unitary conventional equipment used by the apartment building.

Both conventional and on-site systems energy consumptions are highest for Dallas and lowest for Chicago. Thus, the additional energy required for space cooling appears to outweigh any savings in space heating energy when the store is sited in relatively warmer climates. This is characteristic of buildings which major energy loads are internal (derived from people, lighting, equipment, etc.) rather than external (climate related).

Hospital

Fuel cell and conventional system energy consumptions for the hospital are shown in Figure 6-6. Energy savings by the fuel cell system are higher for the hospital than for either of the two previous buildings. This is largely due to the high heating requirements and high load factors of hospitals. Both space and hot water heating requirements are met more efficiently by the fuel cell integrated energy systems.

Total energy consumptions for the fuel cell and gas/electric systems vary only slightly from one location to another (although the mix of gas and electric energy does vary for the gas/electric system). However, energy consumption for the all-electric system is noticeably higher for Chicago and lower for Dallas, relative to Washington, D.C., reflecting these sistes' higher and lower heating requirements, respectively.



SYMBOLS: As Defined in Figure 6-1.

FIGURE 6-6. Annual Energy Consumption: Hospital

6.2 Sensitivity of Base Case Results to Alternative Inputs and Assumptions

Economic and energy analyses were repeated in a number of cases to assess the sensitivity of the results presented in Section 6.1 to alternative input assumptions. It was found that the economic feasibility of the on-site fuel cell system is quite sensitive to changes in electricity and gas prices and investment tax credit, but quite insensitive to fuel cell purchase cost and the type of building ownership that is assumed. Also, it was found that thermal storage had little effect on the economic attractiveness of the fuel cell systems, and only a small amount of energy was saved using storage. The specific assumptions made and results obtained are described below.

6.2.1 Electricity Price

In order to assess the quantitative effect of a different electricity price on the life cycle cost savings of the fuel cell systems relative to the two conventional systems, a range of electricity prices was assumed for the Washington store with a Type C fuel cell system. Figure 6-7 depicts this cost variation graphically for electricity prices ranging from 30 to 85 mills/kWh. All other inputs were held at their base-case levels. As the figure clearly shows, the breakeven electricity price for the Type C fuel cell system versus the all-electric system is 39 mills/kWh, slightly lower than the base case price of 41.7 mills/kWh. When compared to the gas/electric system, however, the breakeven price is 58 mills/kWh, approximately 40% higher than the base case price. As these breakeven prices are exceeded, the cost savings get progressively higher. For electricity prices below the breakeven levels, on the other hand, savings become negative rapidly. Probably the most relevant portions of these curves (graphs) are those which correspond to price variations within 10 to 25% of base case values. Larger price variations could occur, of course, but probably not without concurrent changes in the price of gas.

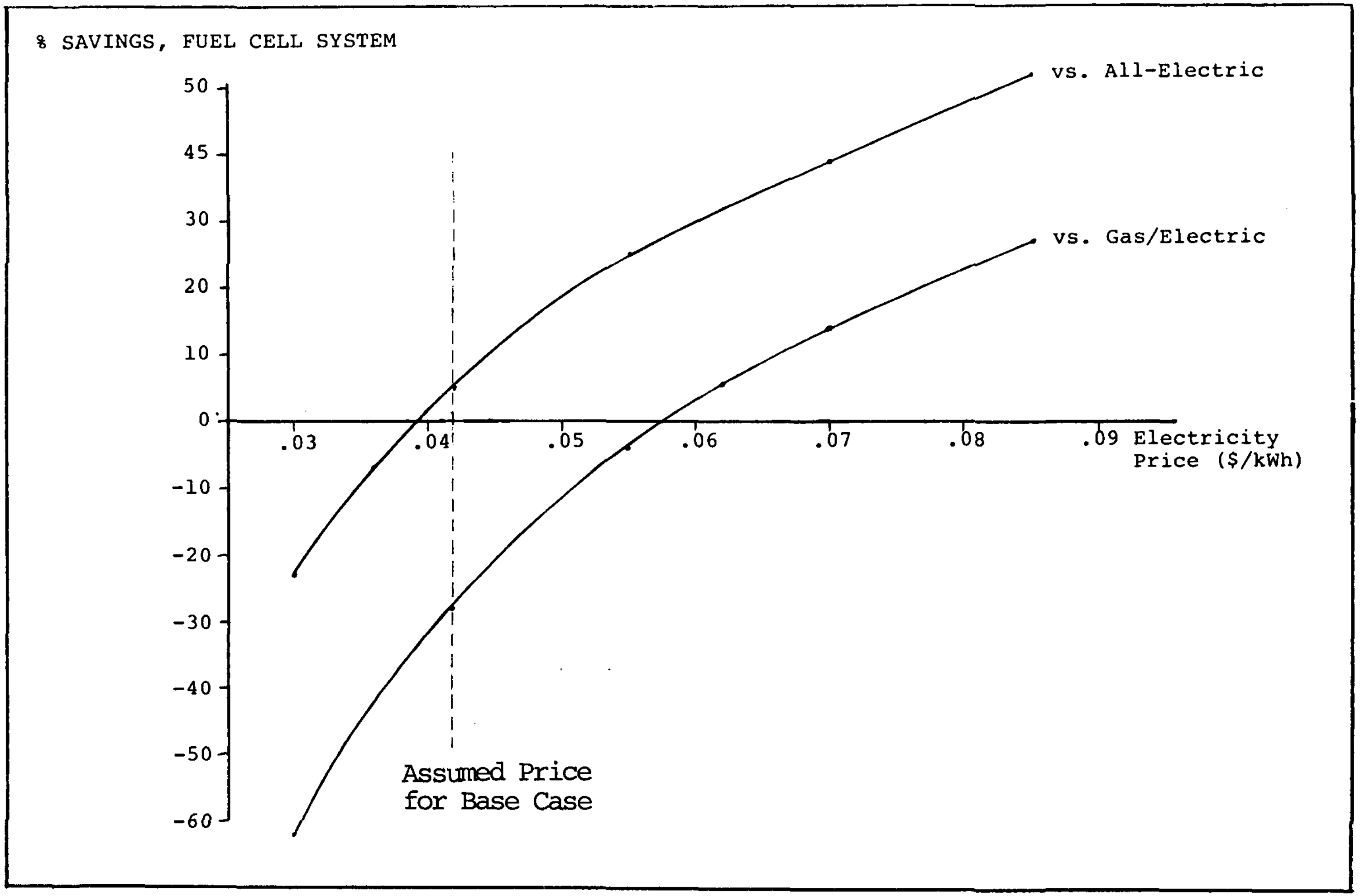


Figure 6-7. Sensitivity to Electricity Price: Retail Store, Washington, D.C., Type C Fuel Cell

6.2.2 Gas Price

A similar assessment was made of the sensitivity of fuel cell system cost savings to a different assumed gas price. The results of this assessment are plotted in Figure 6-8 for the same building, location, and fuel cell type for gas prices ranging from 1.4 to 5.7 $\$/10^6$ kJ. As in all the sensititivy analyses, all other inputs were held at base case levels. In this case, of course, increasing prices result in decreased savings, and vice versa. The base case price is 2.86 $\$/10^6$kJ and the two break-even prices are 3.03 $\$/10^6$kJ, relative to the all-electric system, and 1.70 $\$/10^6$kJ, relative to the gas/electric system. As Figure 6-8 shows, cost savings decrease in (approximately) the same proportion as gas prices increase.

6.2.3 Fuel Cell Purchase Price

Prior to completing the base case analyses, it was felt that changes in fuel cell purchase cost would likely have a large effect on the economic feasibility of fuel cell, on-site integrated energy systems. However, when the assumed fuel cell purchase cost was increased by 10% over the base case value, the fuel cell systems levelized annual costs increased by less than 1%, and costs for the low-rise apartment buildings increased by only about 0.5%. The exact increases that resulted for each application are shown in Table 6-1 for the Type C fuel cell system in Washington, D.C. Based on these results, it may be concluded that even significant reductions in fuel cell capital cost are unlikely to have a large effect on the cost of ownership of a fuel cell integrated energy system. However, fuel cell purchase cost will be an important factor in the selection of a building energy system, whenever the selection is based on "first-cost" rather than life cycle cost.

6.2.4 Investment Tax Credits

For the various reasons discussed in Chapter 5, it was decided not to assume an investment tax credit for any of the three building types for the base case analyses. An investment

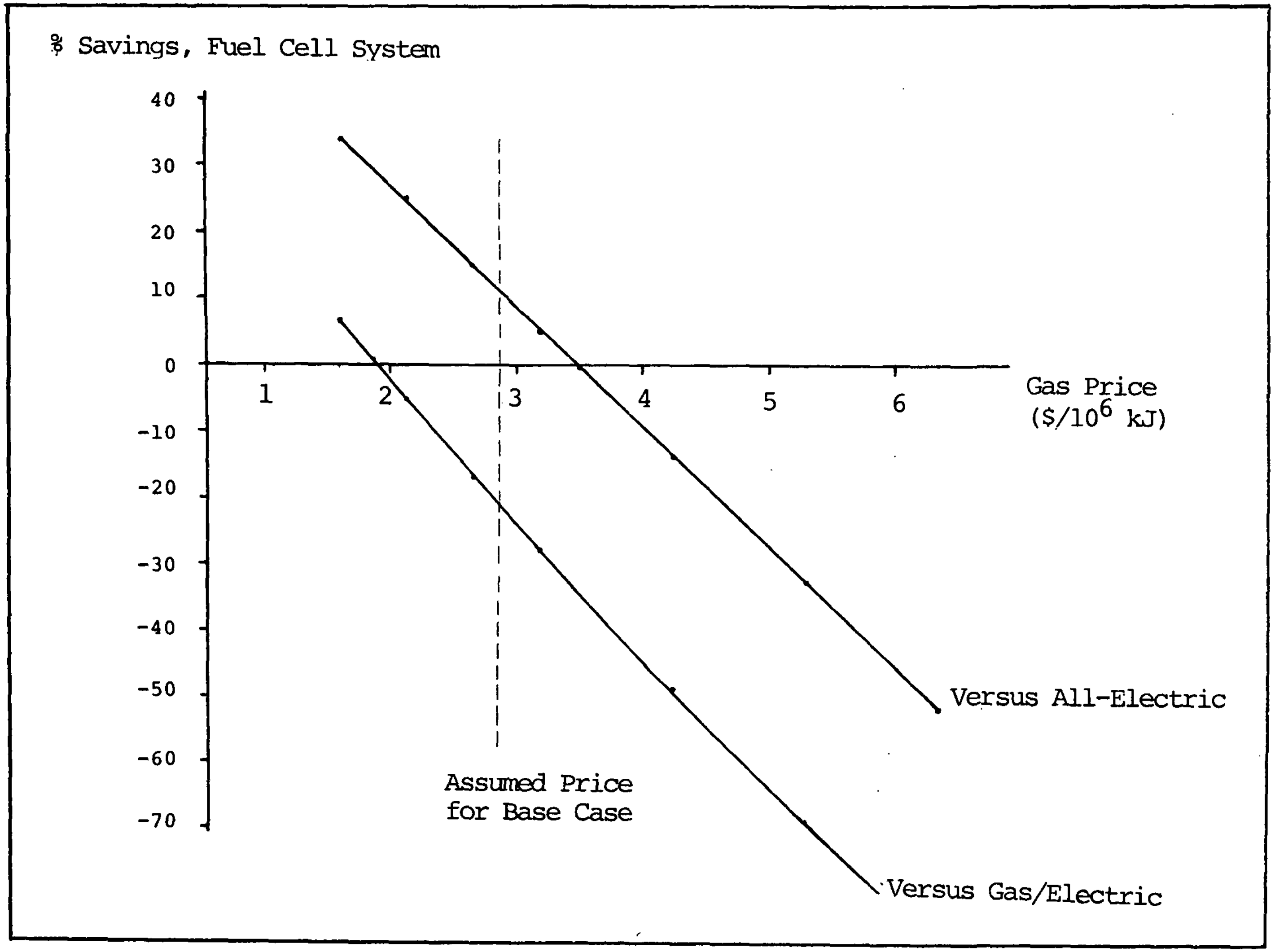


Figure 6-8. Sensitivity to Gas Price: Retail Store, Washington, D.C., Type C Fuel Cell

TABLE 6-1

RESULTS OF SENSITIVITY STUDY

VARIABLE	PERCENT CHANGE IN LEVELIZED ANNUAL COSTS*		
	RESIDENTIAL	STORE	HOSPITAL
• Electricity Price (+10%)			
• OS/IES	0	0	0
• All-Electric	8.1	8.2	10.7
• Gas/Electric	5.2	7.5	6.0
• Gas Price (-10%)			
• OS/IES	-4.4	-6.2	-7.4
• All-Electric	0	0	0
• Gas/Electric	-2.1	-1.0	-4.1
• Fuel Cell Purchase Credit (OS/IES only) (0 → 10%)	-0.47	-0.82	-0.53
• Investment Tax Credit (OS/IES only) (0 → 10%)	-3.8	-2.4	-0.89
• Alternate Ownership			
• OS/IES	-0.21	+1.4	---
• All-Electric	-0.23	+0.63	---
• Gas/Electric	-0.23	+0.25	---
(Type of Ownership)	(Limited Partnership)	(Corporation)	---

*All OS/IES results are for system with Type C fuel cell in Washington, D.C. location.

tax credit could become available, however, based on a government policy decision to promote more efficient building energy systems. In order to assess the effect that such a tax credit would have on integrated energy systems feasibility, therefore, an investment tax credit of 10% was assumed for the fuel cell systems alone, and the effect on system life cycle cost was evaluated. Table 6-1 lists the results of these assessments for each building type for the Type C fuel cell system in Washington, D. C. As the table shows, the tax credit has the greatest effect on the life cycle cost of the apartment building integrated energy system. A cost reduction of about 4% results. Smaller cost reductions result for the store and hospital, because of the proportionately smaller fraction of their overall life cycle cost that is attributable to capital investment.

6.2.5 Alternative Ownership Assumption

As mentioned in Chapter 5, two common types of ownership were identified for both low-rise apartment buildings and retail stores. For the base case analyses, direct ownership was assumed for the apartment building, and a limited partnership for ownership of the retail store. No alternative ownership was assumed for the hospital, since a clear majority of all hospitals are non-profit corporations. In assessing the effects of different ownership assumptions for the apartment building and store, the most common ownership alternative was evaluated for each. Specifically, the assumed ownership for the apartment building was changed to limited partnership while ownership for the store was changed to corporation. Table 6-2 shows the specific financial data associated with each type of ownership for these two applications, as compared with the base case data values.

The percent change in fuel cell and conventional system levelized annual costs for apartment building and retail stores are listed in Table 6-1 for the above alternative ownership assumptions. The most notable aspect of these results is the relative insensitivity of

TABLE 6-2

FINANCIAL DATA FOR ALTERNATE OWNERSHIP ASSESSMENT

ECONOMIC DATA ITEM	LOW-RISE APARTMENT BUILDING		RETAIL STORE	
	DIRECT OWNERSHIP	LIMITED PARTNERSHIP	LIMITED PARTNERSHIP	CORPORATION
• Ratio of Debt Capital to Total Capital	.80	.75	.75	.75
• Cost of Debt				
• With Inflation	.125	.117	.120	.120
• Without Inflation	.042	.034	.037	.037
• Ratio of Common Equity to Total Capital	.20	.25	.25	.25
• Cost of Common Equity				
• With Inflation	.100	.110	.110	.130
• Without Inflation	.019	.028	.028	.046
• Composite Federal and State Income Tax Rate	.42	.40	.45	.50
• Building Design and Construction Time, Years	3.0	3.0	3.5	3.5

the base case costs to the assumed changes in building ownership and financing. Apartment building annual costs decreased by less than 1/4% when the assumed ownership was changed from direct ownership to limited partnership, while costs for the retail store increased by up to 1.5%. It is also interesting to note that both of the assumed ownership and financing options are more favorable to the conventional systems than the fuel cell systems.

6.2.6 Evaluation of Thermal Storage Costs and Benefits

Although the integrated energy system designs described in Chapter 4 did not include thermal storage, such a design option was evaluated for all three applications in Washington, D.C. Thermal energy storage has the potential to improve energy performance by storing energy that otherwise would be rejected. It also has a smoothing effect on equipment operation, permitting operation at higher levels during low load periods, while storing the energy for subsequent peak shaving. Finally, when thermal storage is used for peak shaving, it permits equipment size reductions, which in turn improve part-load efficience. Thermal storage systems can be operated on daily, seasonal, or annual cycles, each of which require different storage sizes. For this study it was assumed that thermal storage would be located at the thermal output of the fuel cell and would operate on a daily cycle.

In order to determine the required storage size and the energy savings potential of thermal storage for each application, the computer simulation model described in Chapter 4 was modified to determine energy transfers into and out of storage at each hour of each day and to reduce boiler operation and fuel cell heat rejection accordingly. This process allows both the required storage size and the annual energy savings due to storage to be determined, as shown in Figure 6-9.

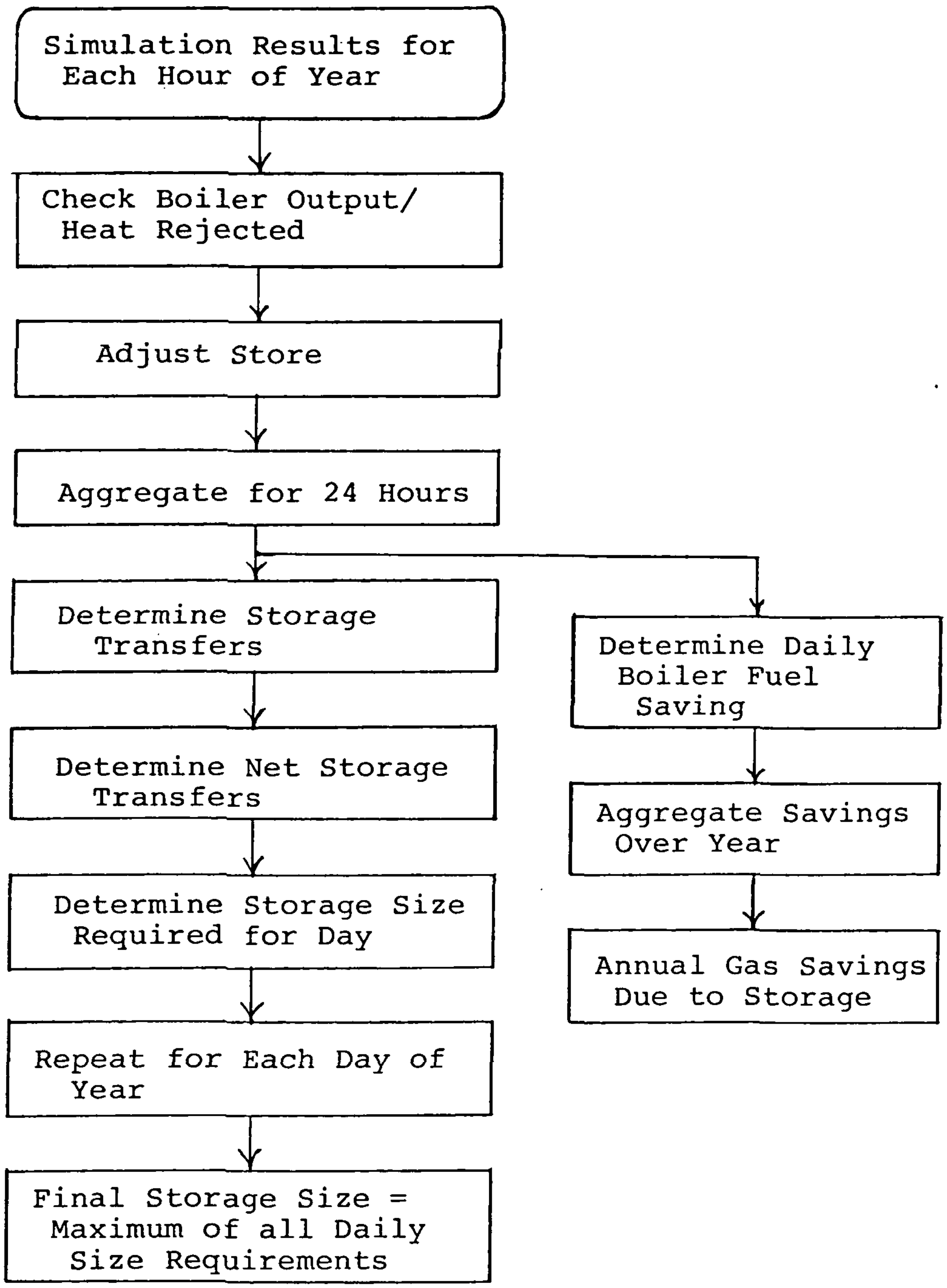


Figure 6-9. Thermal Storage Assessment

The results of the thermal storage assessment are presented in Tables 6-3 and 6-4. Table 6-3 shows the energy savings for each building and fuel cell type, while Table 6-4 shows the corresponding cost saving. As Table 6-3 indicates, the energy savings due to storage are significant, though not large, ranging from approximately 0.6% to 4% of annual base case fuel use. Gas savings are greatest for the apartment building (approximately 3.5%) and smallest for the store (approximately 0.65%). The levelized annual cost savings, as shown in Table 6-4, are negative, except for apartment building, which shows a 1% savings. Both the store and hospital show annual cost increases of 3% and 2%, respectively. Based on these results and the assumed capital costs for thermal storage, the use of thermal energy storage is not recommended for the store or hospital applications. Storage does appear to be attractive for apartment buildings, however, although its use will increase the initial (capital) cost of the fuel cell system still further.

TABLE 6-3

RESULTS OF STORAGE SIZE AND ENERGY SAVINGS

(Location: Washington, D. C.)

BUILDING	TYPE OF FUEL CELL	SIZE OF STORAGE (10^6 kJ)	GAS SAVED (10^6 kJ)	AS % INPUT ENERGY
APARTMENT	A	3.0	204.7	3.2
APARTMENT	B	2.4	191	3.7
APARTMENT	C	1.2	195.2	3.5
STORE	A	12.9	194.1	0.65
STORE	B	13.2	151.9	0.58
STORE	C	20.9	488.5	1.70
HOSPITAL	A	38.9	882	0.95
HOSPITAL	B	45.5	2730.3	3.47
HOSPITAL	C	41.3	1417.9	1.67

TABLE 6-4

ASSESSMENT OF THERMAL STORAGE

(Type C Fuel Cell, Washington, D.C.)

Case	Storage Size (10^6 kJ)	Capital Cost of Storage ($1,000)	Annual Savings in Gas to Boiler (10^6 kJ)	Annual Gas Cost Savings ($)	Levelized Annual Savings (% Change in LAC
Low-Rise Apartment Building	1.17	5.68	388	747	380 (1.03%)
Retail Store	20.9	101.6	489	1,539	-5,052 (-2.77%)
Hospital	41.3	200.0	1,419	4,477	-9,442 (-2.07%)

CHAPTER 7

ON-SITE FUEL CELL SYSTEM WITH UTILITY TIE-IN

In addition to designing and analyzing on-site fuel cell systems for stand-alone operation, an assessment was made of the costs and benefits of maintaining an interconnection between the on-site system and an electric utility. Such an interconnection permits a reduction in the required amount of reserve fuel cell capacity. However, the building owner must pay a standby charge for this service, plus a demand and energy charge for all electricity purchased during fuel cell outages. This chapter discusses how the fuel cell system design is affected by grid interconnection, describes the assumed costs of interconnection, and evaluates such operation relative to stand-alone operation, first under the assumption that the on-site system does not sell excess power to the utility and then for the case where power sales to the utility are permitted.

7.1 On-Site System With Utility Tie-In But No Power Sales

As stated earlier, the primary advantage of interconnecting the on-site system with the utility grid is a reduction in the cost of providing the redundant fuel cell capacity required to meet the electrical service reliability goal. If the on-site system is not permitted to sell power to the utility, this cost reduction is the sole benefit of grid interconnection, while the cost of interconnection will vary, depending on the specific utility's rates for standby service. Theoretically, of course, if a grid connection is maintained, the on-site facility could be sized to an electrical capacity somewhat lower than the building's annual peak, with the utility meeting all electrical demands in excess of the on-site peak capacity. However, it was required for this study that utility power be purchased only during unscheduled outages of the on-site fuel cell system.

Thus, fuel cell capacity must always be either equal to or greater than the anticipated peak electrical demand of the building which it serves.

In determining the fuel cell system capacity and required amount of utility backup, maximum use was made of information developed for the reliability analysis of the stand-alone on-site systems. Specifically, during this earlier analysis a number of fuel cell systems that exactly met the specified reliability goal were identified for each building/location combination. As illustrated previously in Table 4-5, each system was composed of from 3 to as many as 15 equally-sized modules. In considering utility backup for a given building and location, one or more modules in each of those module sets were replaced by an equivalent amount of utility standby capacity. This was done only in those instances where the reduced fuel cell capacity would still meet or exceed the annual peak electrical load. This one-for-one exchange of utility backup capacity for fuel cell capacity assures that the reliability of the modified on-site fuel cell system will slightly exceed the reliability goal met by the stand-alone system, since each unit of utility power is provided at higher reliability than the fuel cell capacity it replaces. After making all the substitutions of utility backup for fuel cell capacity that were possible for a given building and location, each option was evaluated, and the lowest cost option selected, as illustrated in Figure 7-1.

In evaluating each of the utility backup options it was necessary to calculate and compare the annual decrease in fixed charges due to the reduction in fuel cell capacity and the annual cost increase for utility backup. The former quantity was computed simply by calculating the decreasing fuel cell plant installed capital cost and multiplying by the appropriate fixed charge rate.

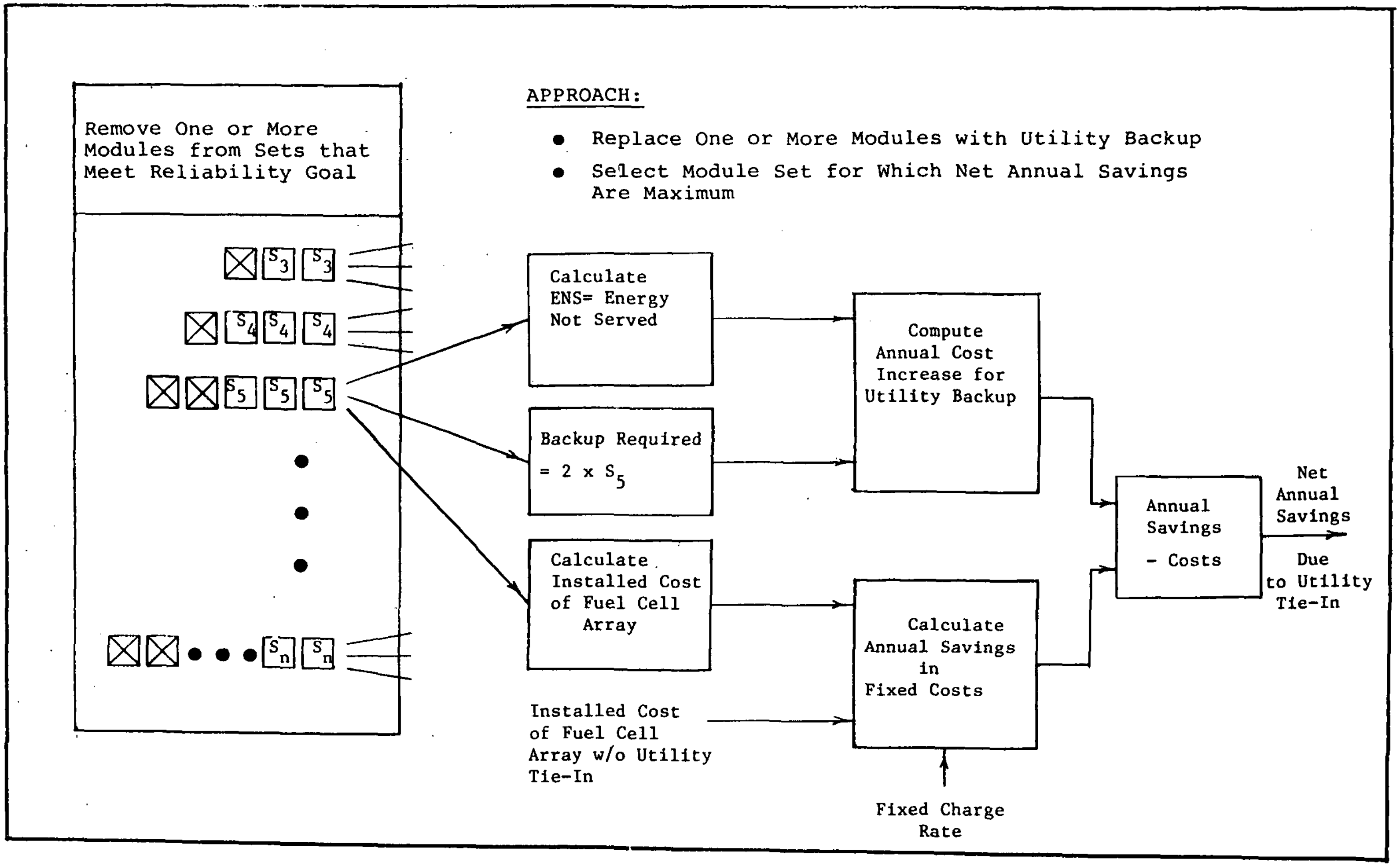


Figure 7-1. Design of Fuel Cell System with Utility Tie-In, No Sales

Utility backup charges were based on an assumed rate schedule for standby service. Specifically, a rate schedule similar to that used by Pacific Gas & Electric Company (PG&E) for standby service (Schedule S-1) was assumed. In accordance with this rate schedule the on-site system must pay a monthly fee of 1$/kW for each month during which standby service is provided and appropriate demand and energy charges for all power purchased during fuel cell plant outages. The assumed demand and energy charges were calculated to be consistent both with the existing demand charges in the three geographic locations and with the assumed national average electricity price used in the previous analyses. The values used were:

- Demand Charge 4$/kW/mo
- Energy Charge 33 mills/kWh

Obviously, the total annual demand charge will depend both on the number of fuel cell plant outages and on the months in which they occur. The total building electricity required but not served by the fuel cell system due to unscheduled outages was calculated by Public Service Electric and Gas Company. However, because the system simulation was deterministic rather than probabilistic, it did not provide an estimate of the times of occurrence or duration of system. Because of this, there was no way of knowing the number of months in which a demand charge would be incurred. For simplicity, it was assumed that each fuel cell system would experience one or more unscheduled outage(s) that would occur in, or span, two different months. Thus, the annual demand charge in each case was

Annual Demand Charge = 4$/kW/mo X 2 mos/yr = 8$/kW/yr

Using the above methodology, fuel cell configurations and utility backup capacities were specified for each building and location, and the respective charges in annual costs to the energy system owner were calculated. The results of these calculations are presented in Table 7-1. As the results show, the savings are positive

TABLE 7-1

IMPACT OF UTILITY TIE-IN WITH NO SALES

(Results for Washington, D.C.)

APPLICATION	% SAVINGS IN LEVELIZED ANNUAL COST		
	TYPE A F.C.	TYPE B F.C.	TYPE C F.C.
RESIDENTIAL	0.83	0.52	0.40
STORE	0.45	-0.18	-0.26
HOSPITAL	0.47	0.33	0.20

in most instances, but the magnitude of these savings are so small as to have an almost negligible effect on the annual costs reported in Chapter 6. As the next section will show, the relative benefits of selling excess power to the utility are more significant.

7.2 On Site-System with Utility Tie-In and Power Sales

The two primary effects of power sales to the utility are an increase in revenue from energy sales and an increase in the amount and cost of gas consumed to produce this additional electricity. For integrated energy systems, however, there also is a less obvious effect, that of an increase in the amount of useful heat produced for on-site consumption. Figure 7-2 shows how the simulation procedure described in Chapter 4 was modified to produce the information required to evaluate all three effects. As the figure shows, two of the more subtle results of producing excess power may be a reduction in the use of supplemental heating equipment and a substitution of absorption for electric compression chilling, both as a result of increased heat production. Required simulation outputs include:

- total excess electrical energy produced
- net increase in gas consumption by fuel cell
- decrease in gas consumption by boiler.

Once these quantities have been calculated the net annual savings due to power sales is computed, as shown in Figure 7-3.

In general, the amount that a utility will pay for self-generated power will be based on that utility's incremental production cost at the time of exchange. Although incremental costs vary continuously throughout the day, the greatest difference in these costs occurs between the so-called "on-peak hours" (assumed for this study to be 8 a.m. to 8 p.m.) and the "off-peak hours" (all other times). Therefore, for each time interval, a single

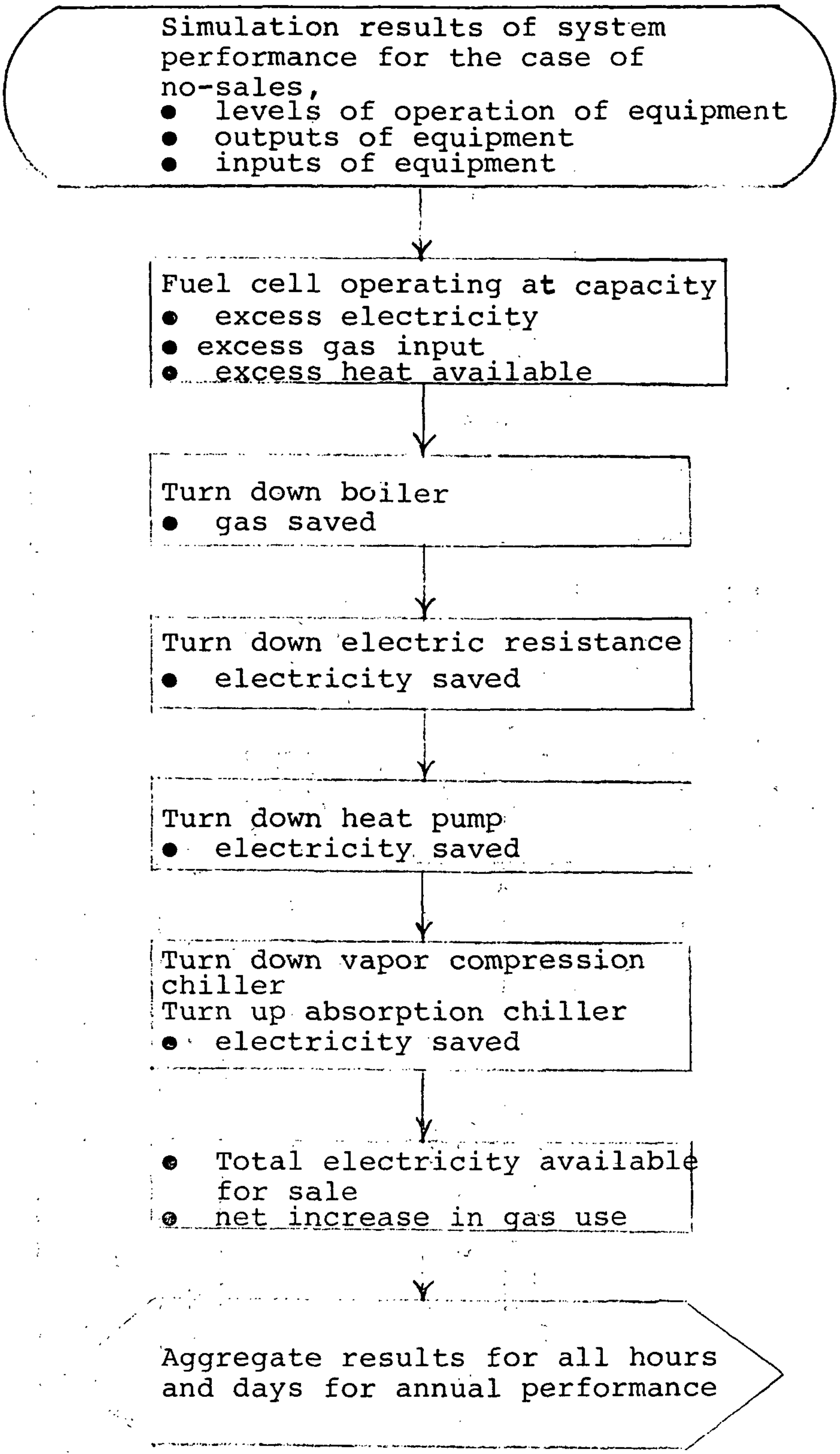


Figure 7-2. Model for Computing the Effect of Sales of Electricity to Utility

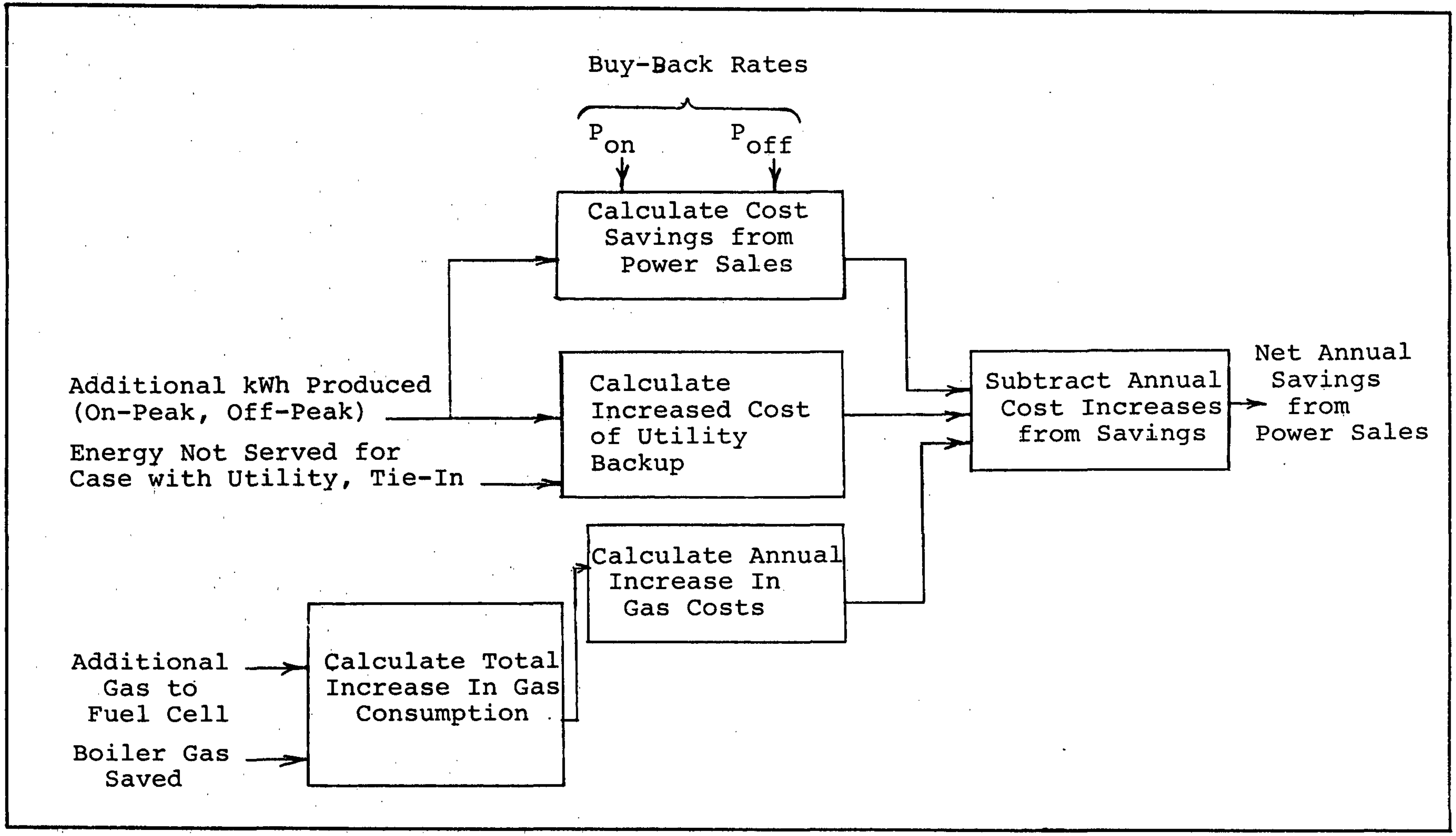


Figure 7-3. Evaluation of Utility Tie-In with Power Sales

"buyback rate" was specified, to represent the average level of incremental production costs over either the on- or off-peak period. The buyback rates used were:

- On-Peak Rate for power sales to utility 28.7 mills/kWh
- Off-Peak Rate for power sales to utility 20.1 mills/kWh

These rates were based on estimates by PSE&G and Mathtech.

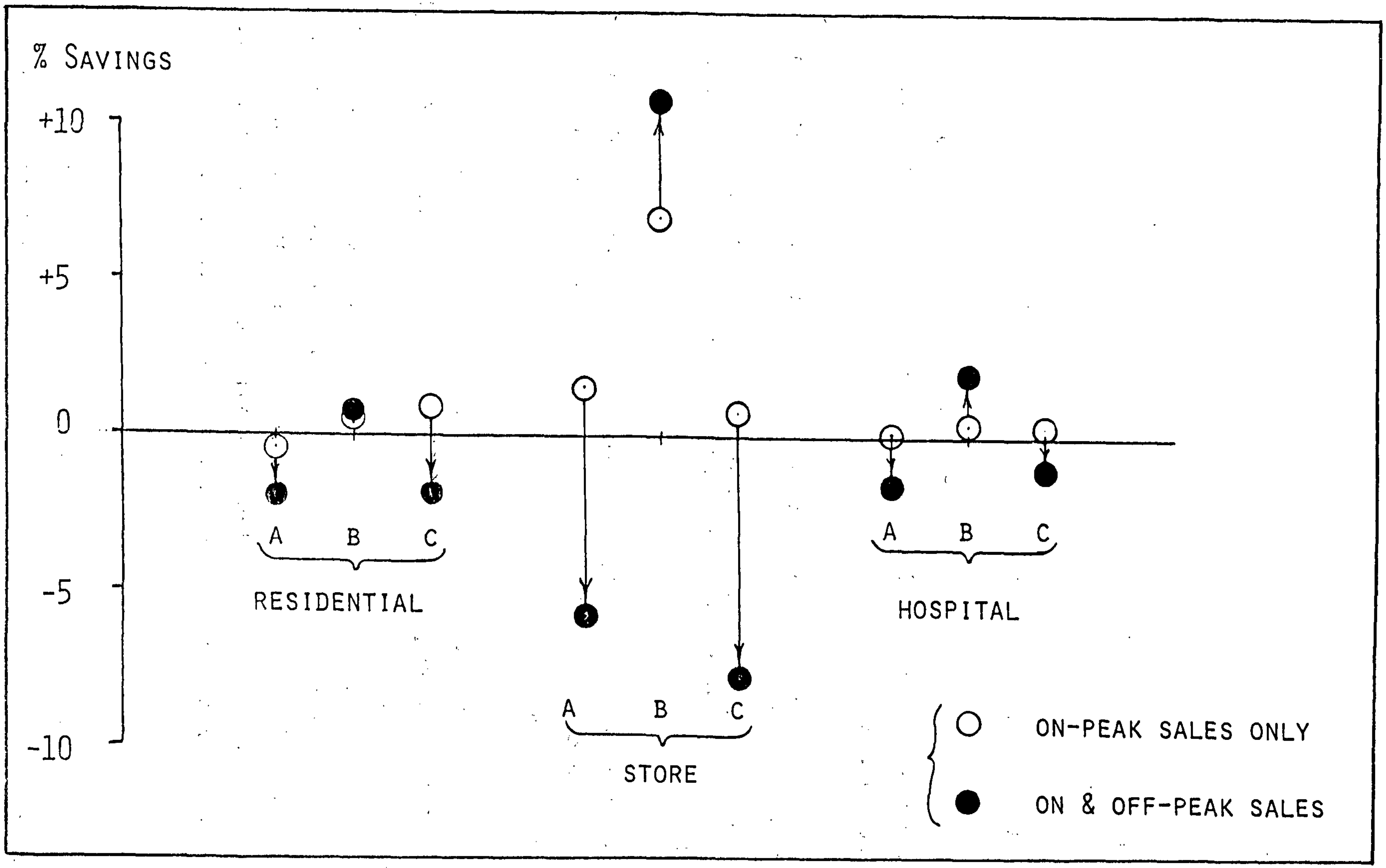
In view of the above rates for power sales to the utility, there are two obvious strategies for operating the on-site fuel cell to produce excess power

- operation at full capacity at all times, selling excess electricity
- operation at full capacity during on-peak period only, with off-peak operating levels determined by building requirements only.

Both strategies were investigated since their relative benefits could not be determined without an assessment of the amount and value of any excess thermal energy produced.

The economic results of these investigations are presented in Figure 7-4 for both on-peak sales and the combined sales. Although the savings for peak hour sales are generally positive, the reduction in cost is not sufficient to warrant a utility connection Savings are greatest for the retail store application because the capacity factor for the retail store's on-site system is significantly lower than those for the other two buildings. (Thus, there is more excess capacity available for sale to the utility.)

In all but two cases, namely the on-site systems for the store and hospital that use a Type B fuel cell, these savings become negative when off-peak sales are combined with peak hour sales. For



Figures 7-4. Impact of Power Sales on Levelized Annual Costs

the store and hospital systems that use a Type B fuel cell, however, the greater efficiency of the Type B fuel cell and the lower price of gas to commercial customers combine to make average off-peak electric energy costs for these two systems lower than the off-peak buyback rate of the electric utility.[1/] Thus, for these two systems it is profitable to sell excess off-peak electricity, and the savings due to power sales are increased.

Table 7-2 lists the respective efficiencies of generating additional electricity for sale to the utility. In calculating these efficiencies the amount of electrical energy produced for sale was divided by the amount of additional gas to the fuel cell less the reduction in gas to the boiler. In general, the resulting efficiencies are the same or only slightly higher than the three fuel cells efficiencies of producing electricity alone.

Several conclusions may be drawn from the above results. Specifically, for the buildings considered here and the assumed buyback rates:

- the sale of excess power during on-peak hours is marginally attractive for most applications but may be worthwhile for the retail store and Type B fuel cell.
- The sale of excess power during on- and off-peak hours combined is generally unattractive, except for the store and hospital systems that employ a Type B fuel cell.

In addition, from an energy supply perspective, any benefits that can be realized from the production of off-peak electricity using fuel cells must be weighed against the unfavorable effects of displacing base-load generation that uses coal or nuclear resources.

1/ The apartment building system with the Type B fuel cell purchases gas at the residential price which is 15% higher than the commercial price. Thus, the Type B system for the apartment building has an average off-peak energy cost of 22.0 mills/kWh, while the average off-peak energy costs for the store and hospital are 18.1 mills/kWh and 16.9 mills/kWh, respectively.

TABLE 7-2

EFFICIENCIES OF GENERATING EXCESS POWER FOR SALE TO UTILITY

(Results for Washington, D.C. Location)

APPLICATION	FUEL CELL TYPE	EFFICIENCY OF GENERATING EXCESS POWER	
		ON PEAK SALES ONLY	ON- AND OFF-PEAK SALES
LOW-RISE APARTMENTS	A	.36	.41
	B	.49	.56
	C	.49	.46
RETAIL STORE	A	.38	.41
	B	.49	.54
	C	.37	.40
HOSPITAL	A	.37	.42
	B	.51	.60
	C	.41	.46

CHAPTER 8

CONCLUSIONS

The economic and technical results presented and discussed in Chapters 6 and 7 make it possible to draw a number of conclusions about fuel cell on-site integrated energy systems. Although the conclusions are based on results for only three residential/ commercial applications and three specific buildings, the three applications account for approximately 24% of all residential/ commercial energy use[1/] and each building design was selected to be representative of the broader application class.

As stated previously, the base case study results are those for the fuel cell OS/IES without a utility tie-in. For such systems and the building designs analyzed, the economic results indicate that fuel cell system life cycle costs are:

- 0% to 33% higher than those of conventional low-rise apartment building energy systems
- 13% lower to 26% higher than those of conventional store energy systems
- 5% to 49% lower than those of conventional hospital energy systems.

In every case, the costs for the gas/electric conventional system are at the low end of the conventional system cost range with the all-electric system at the high end. Based on these results, it is concluded that fuel cell on-site, integrated energy systems are economically attractive for hospitals, marginally attractive for retail stores, and generally unattractive for low-rise apartment buildings.

Similarly, the annual energy consumption analysis indicated that fuel cell system energy resource consumptions are:

[1/] Excluding energy use by single-family detached housing.

- 24% to 54% lower than those of conventional low-rise apartment building energy systems
- 8% to 31% lower than those of conventional store energy systems
- 35% to 58% lower than those of conventional hospital energy systems.

In every case, gas/electric system annual energy consumptions are lower than those of the corresponding all-electric system. Based on these results, it is concluded that the use of fuel cell on-site integrated energy systems would greatly reduce consumption in hospitals and low-rise apartment buildings and reduce retail store energy consumption by a lesser amount.

In evaluating fuel cell integrated energy systems, the relative merits of three fuel cell types were compared for each application. Because of its high efficiency and excellent part load performance, the Type B fuel cell is the most attractive, both in terms of energy consumption and life cycle cost. The Type A fuel cell is least attractive, because of its somewhat higher purchase cost and the higher hot water return temperature that is assumed. The Type C fuel cell falls somewhere between these two, having the lowest purchase cost of all three fuel cells but an energy efficiency that is somewhat lower than that of the Type B cell.

Geographic location has a relatively minor effect on the above conclusions. For the apartment building, the fuel cell system is a little more attractive in Chicago, because of the relative efficiency of the integrated energy system in meeting higher heating demands, and in Dallas, because of the high electricity cost for space cooling of the two conventional systems. For the retail store, the relative attractiveness of the fuel cell system is essentially unaffected by changes in geographic location, although energy consumption (and cost) for all five systems increases proportionately with the average temperature of the building site. Finally, for the hospital, the fuel cell system is a little more attractive relative to the all-electric system in Chicago, because of the inefficiency of electric space-heating in such a cold climate, and a little more attractive relative to the gas/electric system in Dallas, because of the inefficiency of operating absorption chillers from a boiler.

Various integrated energy system design and operating alternatives, including utility backup, sale of excess power to the utility, and thermal storage, were evaluated. Utility backup without power sales did not appreciably change the conclusions drawn above, but *power sales to the utility, increased the economic savings of the* fuel cell system by up to 11%. Finally, the costs of thermal storage were generally found to exceed any benefits storage would produce in terms of reduced energy costs. However, the use of storage would reduce annual gas consumption by 1% to 4%.

Sensitivity assessments were made of various input parameters and assumptions. Variations in gas and electric prices were found to have the greatest effects on fuel cell system economic savings, which ranged from 4% to 8%. The effects of a 10% investment tax credit for the on-site systems also were significant. Such a tax credit would cause the life cycle cost for these systems to decrease from 4% for the apartment building to 1% for the hospital, with savings for the store falling in between.

From a purely economic standpoint, either a significant increase in the price of electricity or decrease in the price of gas will be required in order to provide a real incentive for building owners to install fuel cell integrated energy systems in low-rise apartment buildings and retail stores. The incentive for hospitals may already be great enough.

From an energy use standpoint, the resource savings for apartments and hospitals is impressive, while that for stores is relatively modest. What may be more important in this regard, however, is the relative savings in scarce or premium fuels, including oil and possibly gas. If utility electricity is generated primarily with more abundant resources, such as coal and nuclear, the fuel cell systems could be saving total energy at the expense of an increase in scarce fuel consumption. One way of avoiding such a situation would be the development of fuel cells that utilize a clean, coal-derived gas or a biologically-derived gas. However, much uncertainty remains about the costs of such fuels.

APPENDIX A

FUEL CELL CHARACTERISTICS

APPENDIX A

FUEL CELL CHARACTERISTICS

Three types of fuel cells are considered for the analysis in this study. All three fuel cells are of the phosphoric acid type and may be characterized as follows:

- Type A -- Present Generation Fuel Cell
- Type B -- Advanced Technology Fuel Cell
- Type C -- Near-Term Technology Fuel Cell

The Type A and Type C fuel cell power plants are representative of those being developed for commercialization in the 1985 time frame. The Type B fuel cell power plant represents a significant technology advance over the other two types.

All fuel cell power plants considered in this study are assumed to be self-contained units consisting of a fuel processor, a fuel cell power unit, an electrical inverter, a cooling system, and a heat recovery system. All power plants have two sources of recoverable thermal energy: (1) the recirculating coolant loop, which is a high-temperature source, and (2) the reformer and cathode vents, which is a low-temperature source. Heat can be recovered individually from the two sources, as in the Type A fuel cell; or the heat SVC's can be internally combined, as in Types B and C.

The recovery of thermal energy from the heat recovery system is entirely optional and does not affect the fuel cell system operation. Heat which cannot be recovered by the heat recovery system, or heat from the heat recovery system that is not utilized, is automatically removed by the cooling system. The cooling fan is included in the module.

The fuel processor converts the hydrocarbon fuel, assumed for this study to be natural gas, to a hydrogen-rich gaseous stream which is suitable for reacting in the fuel cell.

The electrical inverter converts the d-c electrical output from the fuel cell to regulated a-c. It is also assumed that fuel cell modules will be available with either single-phase or three-phase output at any voltage level, and for this study the fuel cell module capital cost is assumed to be independent of the number of phases or the voltage level provided by the inverter.

Figures A-1 through A-7 show the electrical efficiency of the fuel cell power plant and the amount of recoverable thermal energy (expressed as a fraction of input energy) from the fuel cell power plant.

Table A-1 summarizes the technical performance data.

FIGURE A-1

TYPE A FUEL CELL ELECTRICAL EFFICIENCY

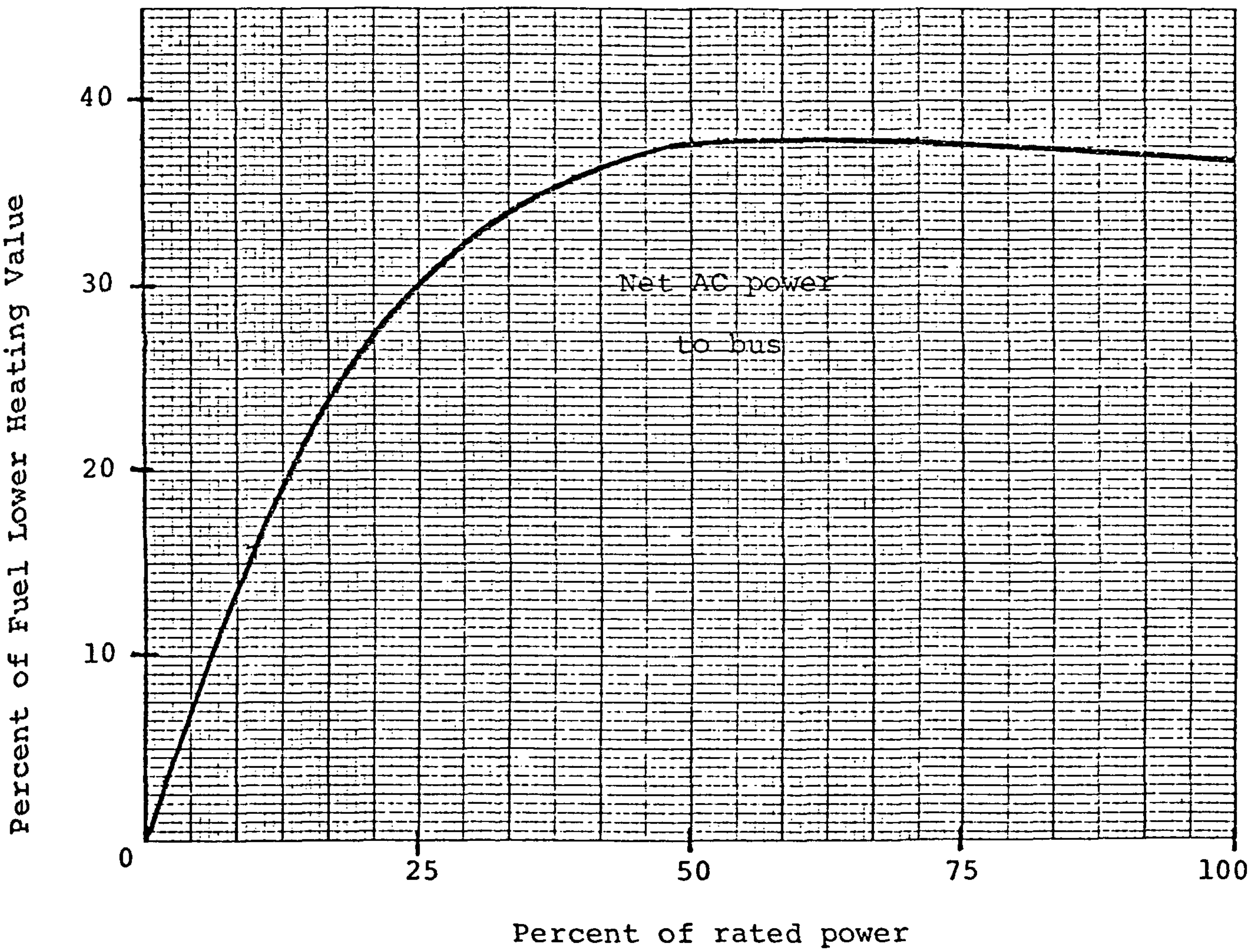


FIGURE A-2

TYPE A FUEL CELL HIGH TEMPERATURE HEAT EFFICIENCY

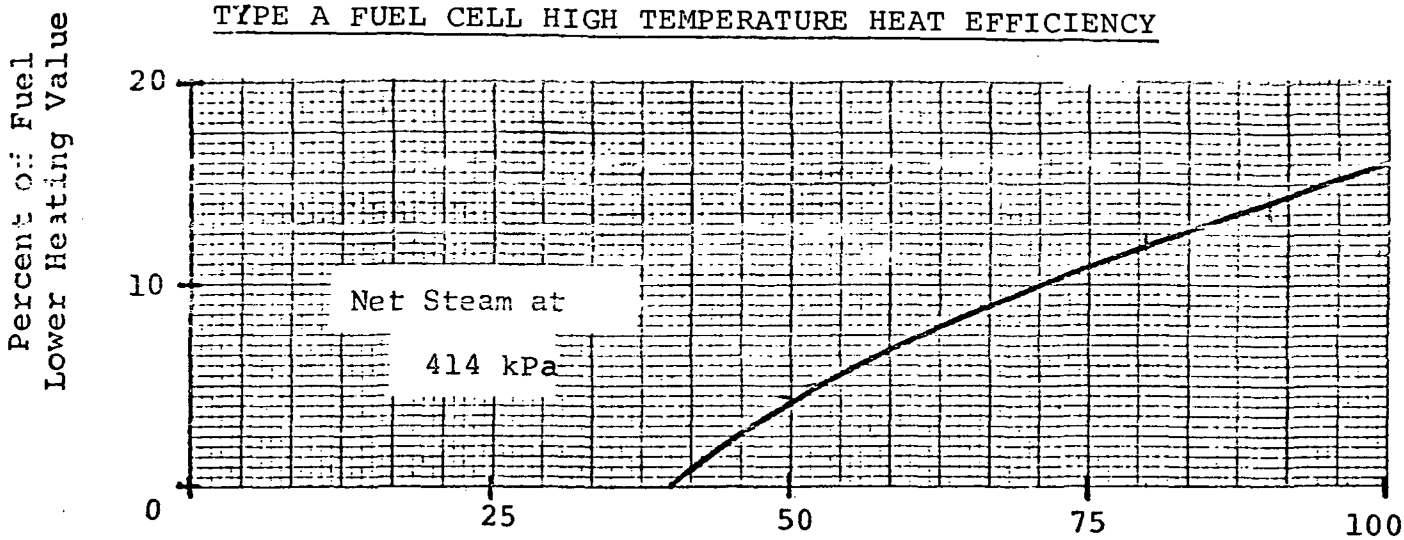
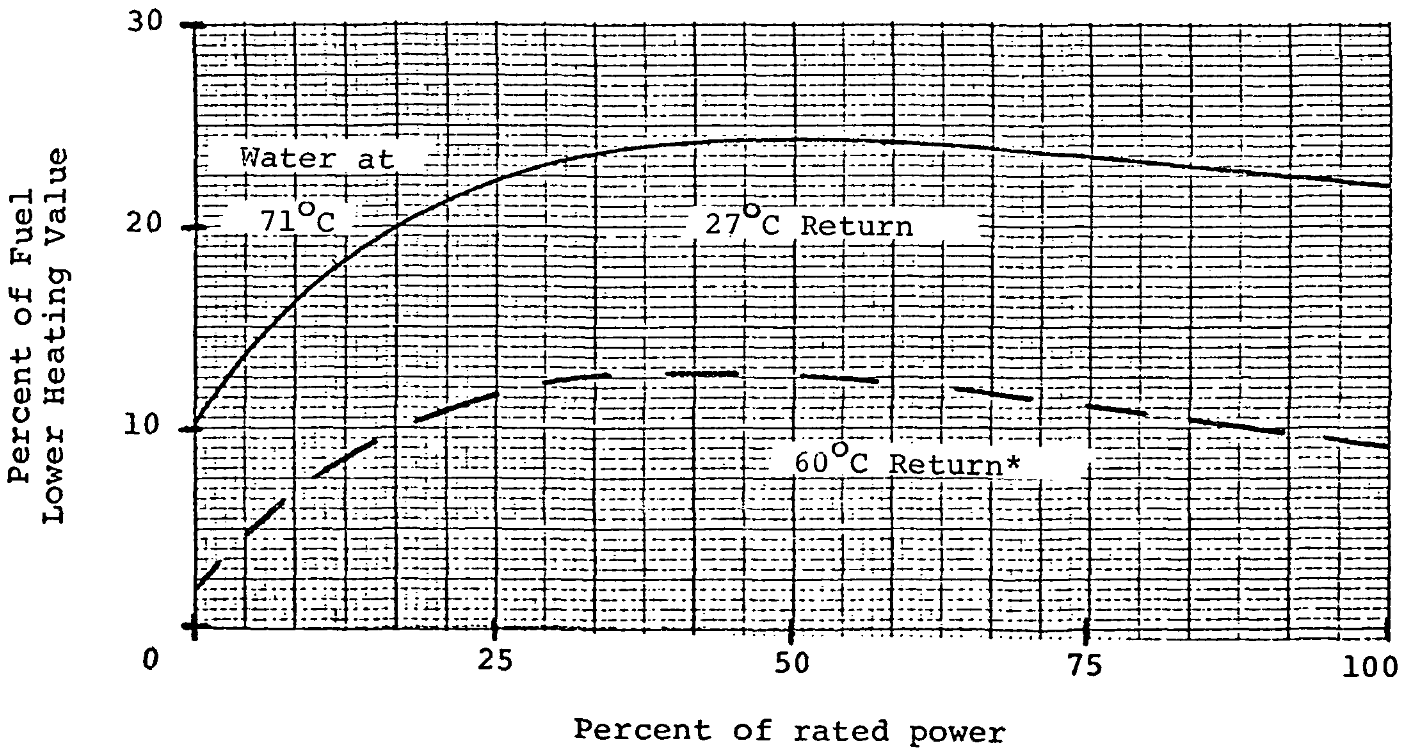


FIGURE A-3

TYPE A FUEL CELL LOW TEMPERATURE HEAT EFFICIENCY



* Denotes return temperature assumed for this study.

FIGURE A-4

TYPE B FUEL CELL ELECTRICAL EFFICIENCY

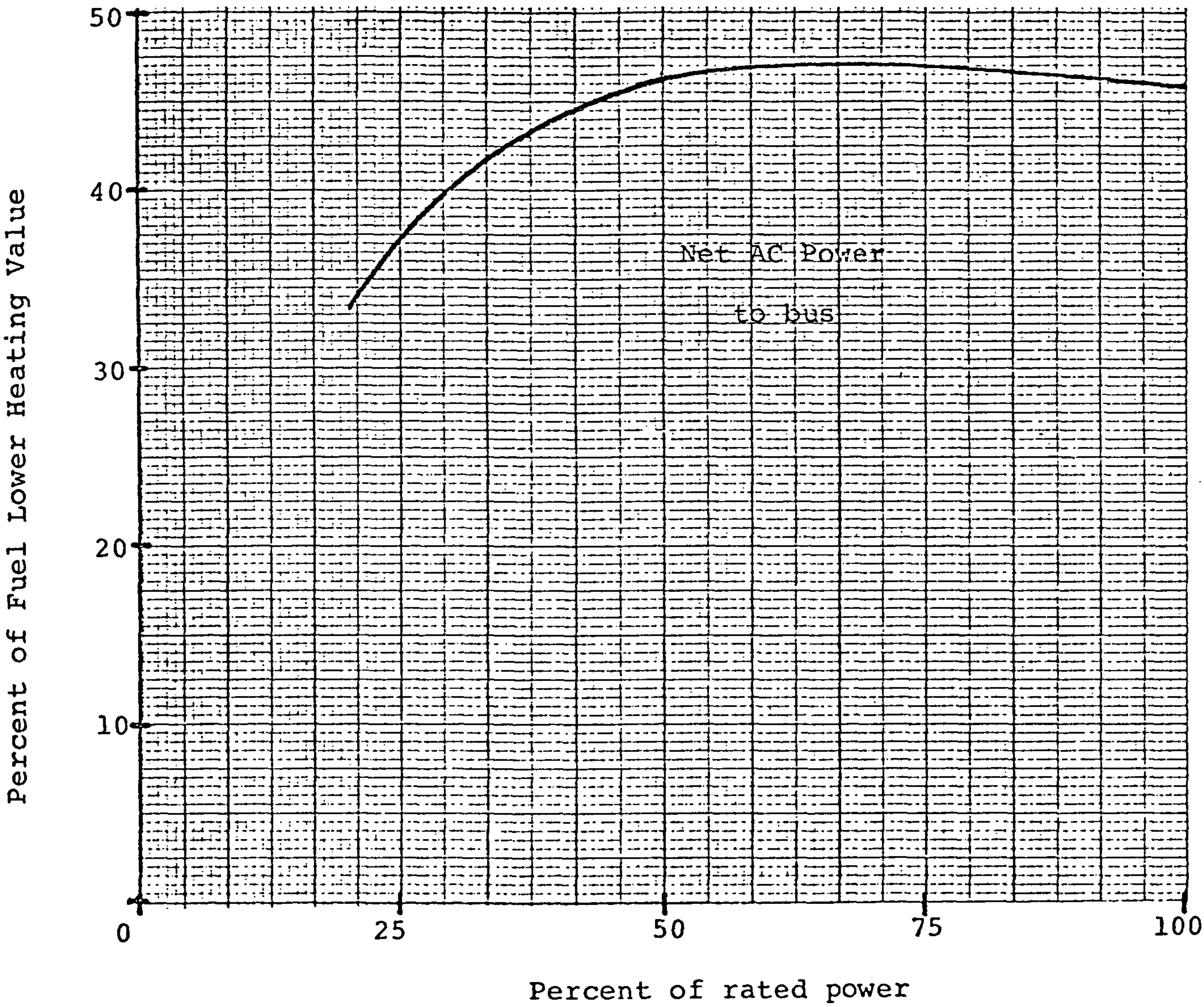


FIGURE A-5

TYPE B FUEL CELL HEAT RECOVERY EFFICIENCY

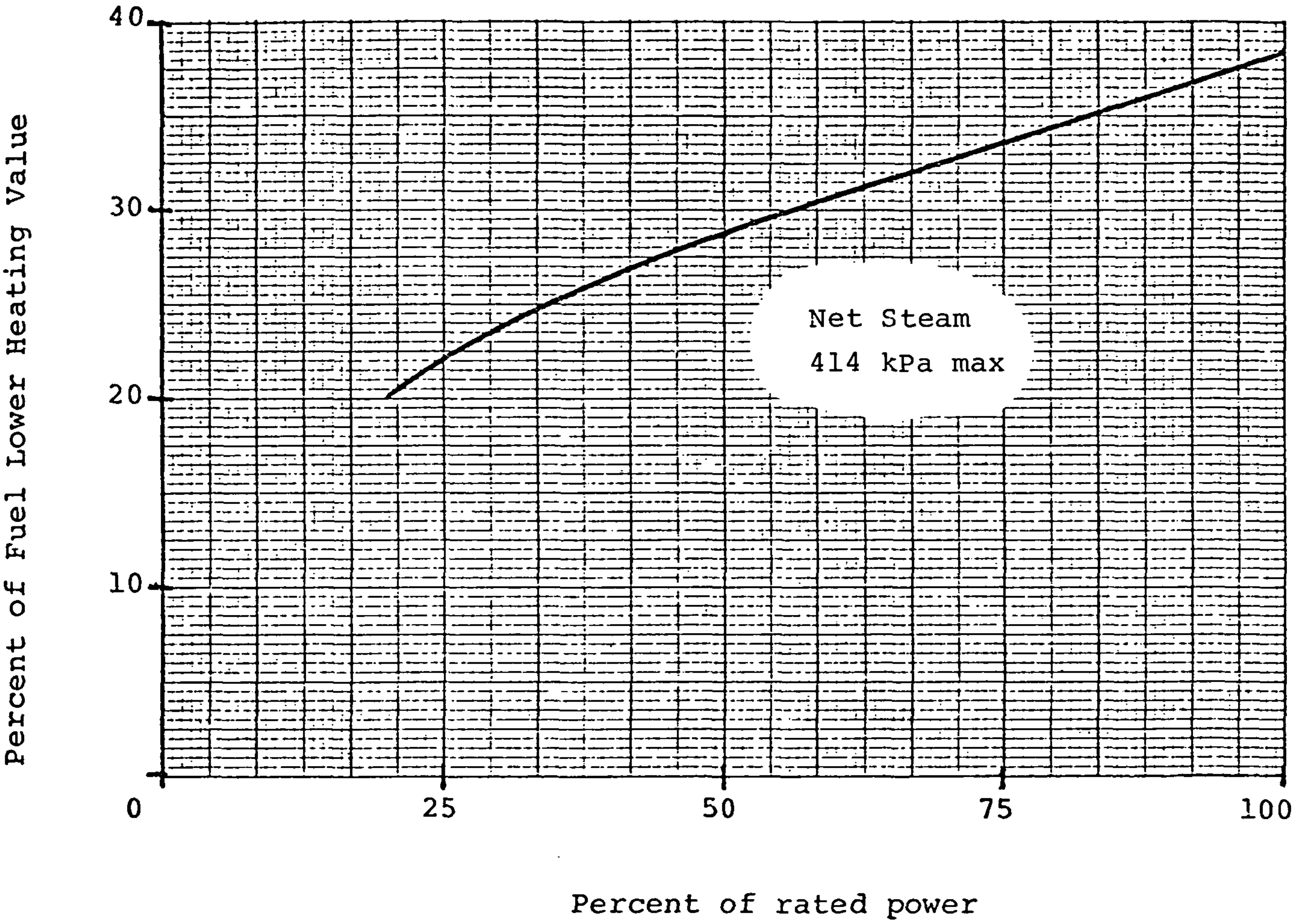


FIGURE A-6

TYPE C FUEL CELL ELECTRICAL EFFICIENCY

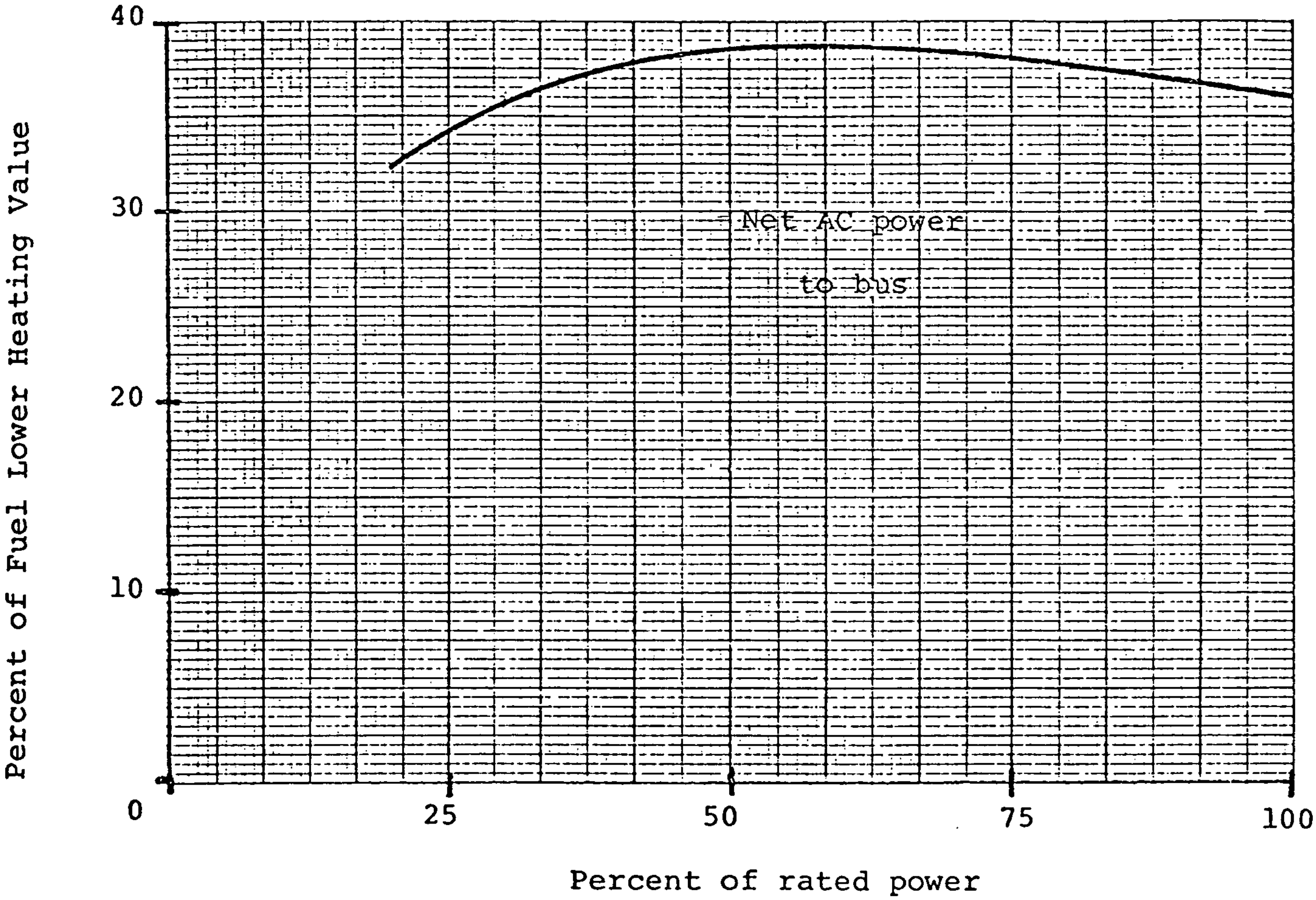


FIGURE A-7

TYPE C FUEL CELL HEAT RECOVERY EFFICIENCY

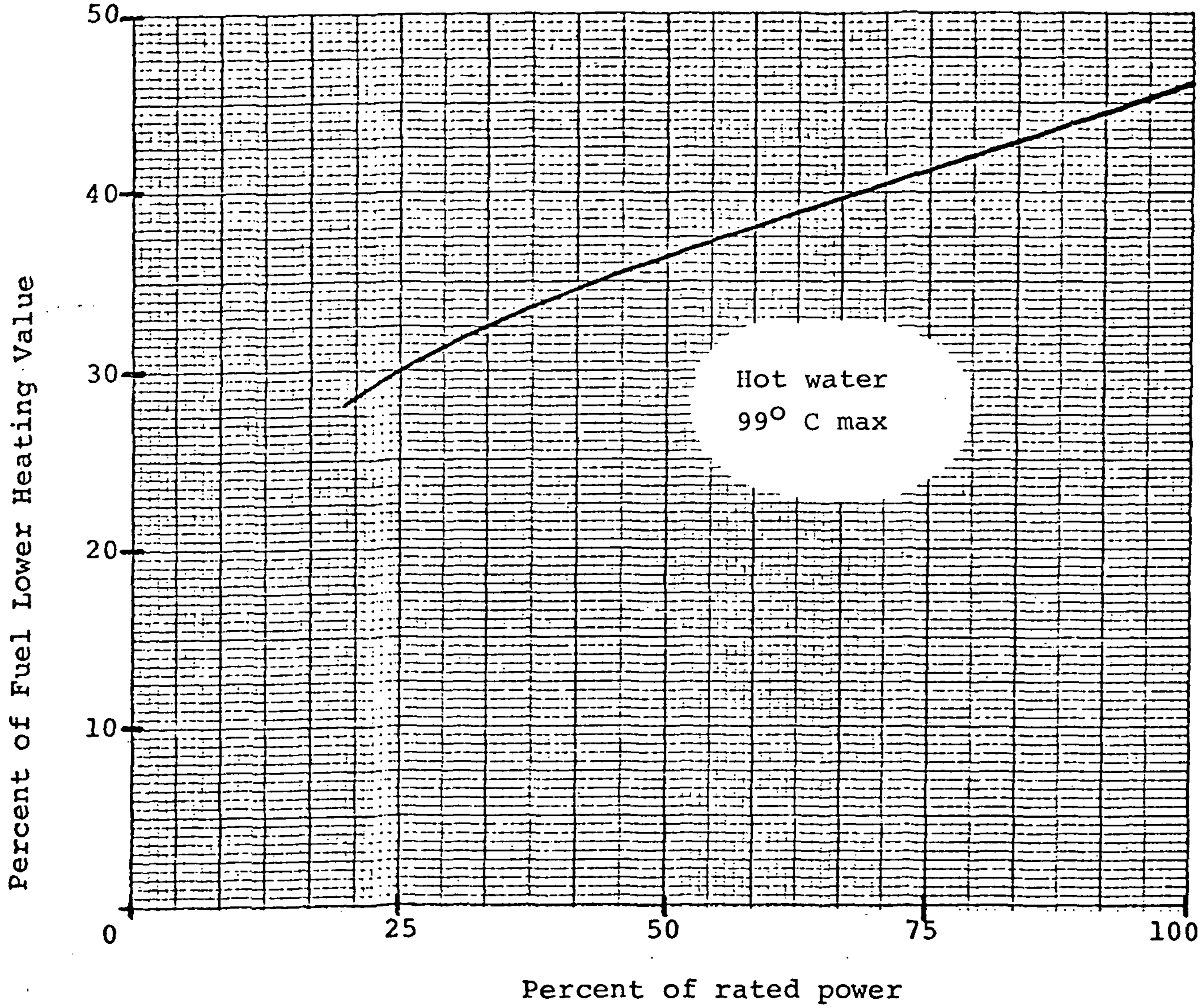


TABLE A-1

FUEL CELL TECHNICAL PERFORMANCE DATA

CHARACTERISTICS	TYPE A	TYPE B	TYPE C
Nominal Operating Temperature, °C	190 ± 14	204 ± 14	176 ± 14
Fuel	Natural Gas	Natural Gas	Natural Gas
Mechanical Characteristics:			
Specific Weight, kg/kW	68	77	68
Footprint, M^2/kW	0.1	0.1	0.12
Height, M	2.0	2.0	2.1
Interface Requirements:			
Fuel Line, SCMH/kW (max flow)	0.33	0.33	0.33
Cooling Air, SCMH/kW2/ (for interior installations only)			
For No Heat Recovery	260	212	43
For Max Heat Recovery	58	58	43
Exhaust2/ (for interior only), SCMH/kW	8.5	8.5	29
Minimum Power, % of Rated	0	29	20
Maximum Power, % of Rated	100	100	100
Maximum Hot Water Delivery, Temperature °C	71	---	93
Maximum Steam Delivery Pressure, kPa	414	414	---
Minimum Module Size, kW3/	5	5	5
Maximum Module Size, kW3/	300	300	300
O&M Cost, mills/kWh	6	6	6
Forced Outage Rate	0.03	0.03	0.03
Purchase Price (1978 $) for fuel cell with capacity of X kW	$615 \cdot x^{0.93}$	$463 \cdot x^{0.93}$	$420 \cdot x^{0.93}$

1/ Natural gas was the fuel assumed for this study. Other fuels are possibl[e] however, minor modifications to the fuel processor may be required if a different fuel is used.

2/ The cooling air stream and the exhaust stream may be combined in a common duct.

3/ Any size (to within 1 kW) between the minimum and maximum sizes was assum[ed] to be available.

APPENDIX B

DESCRIPTION OF STUDY BUILDINGS

APPENDIX B

DESCRIPTION OF STUDY BUILDINGS

B.1 Low-Rise Apartment Building

B.1.1 Summary Description of Selected Building

A. Name and Location:
Sodders Road Apartments
Salem, New Jersey

B. Form: Two-story rectangular structure, consisting of 12 apartments on each floor. Each apartment consists of a living room, dining area, kitchen, 2 bedrooms, and bath with laundry facilities. Each apartment has its own entrance from the exterior.

C. Size: The total gross area is 20,496 sq. ft. Each dwelling unit is 854 gross sq. ft.

D. Construction: Wood stud walls, second floor framed with wood joists, wood roof truss system. The first floor is a concrete slab on grade. The roof is sloped and consists of asphalt shingles on plywood sheathing over the wood trusses. Batt insulation is installed at the bottom chords of the trusses (second floor ceiling). The perimeter walls consist of 4" brick 2" x 4" wood studs with batt insulation, and a finished interior layer of 1/2" drywall. Party walls between units are 8" concrete masonry units.

E. Building Orientation and Floor Plan: See Figure B-1.

B.1.2 Modifications

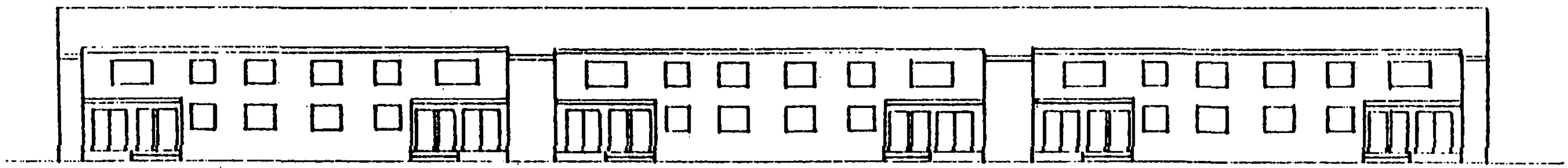
The base design was modified by expansion from 12 dwelling units per building to 24 units to provide a total predicted load on the order of 100 kW. This is a reasonable design; the number of units per building is often the result of site considerations. While two 12-unit buildings would have approximately the same energy needs, the use of a fuel cell central plant suggest a single building to eliminate the construction cost and energy losses of transmission lines.

B.1.3 ASHRAE 90-75 Compliance

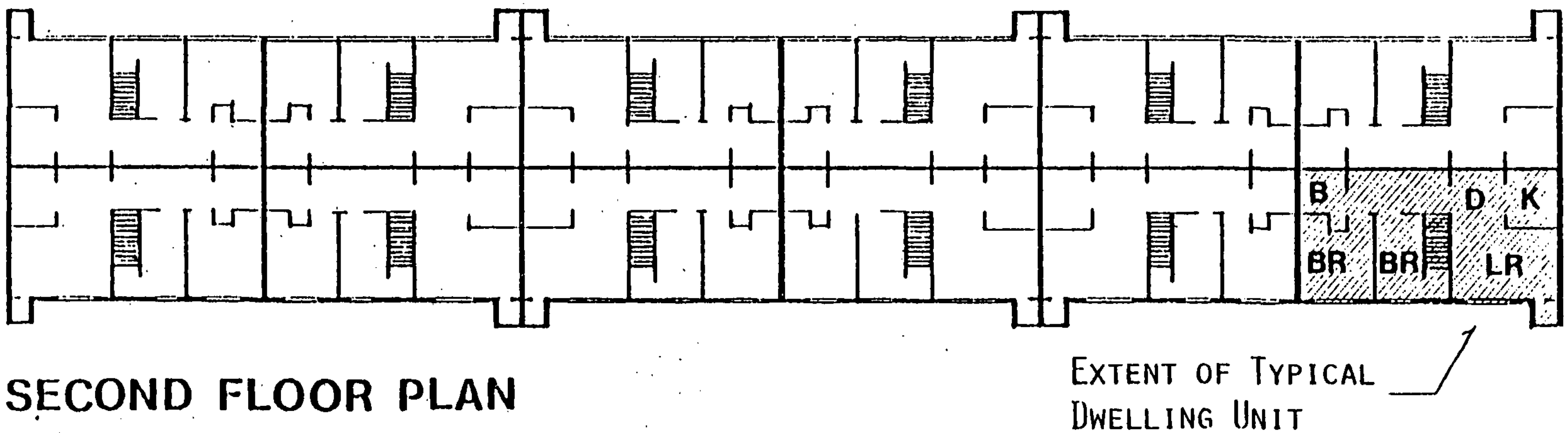
The building envelope complies with ASHRAE-90 for all locations. The HVAC systems, both original and re-designed, comply with ASHRAE 90-75. Lighting was adjusted to comply

FIGURE B-1

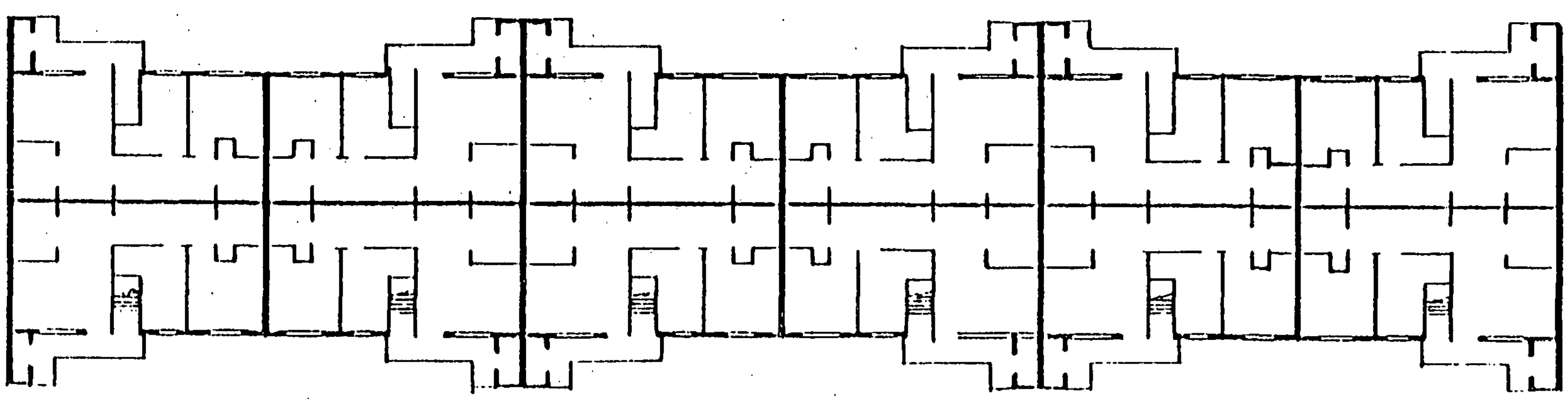
LOW-RISE APARTMENT BUILDING



NORTH & SOUTH ELEVATION



SECOND FLOOR PLAN



GROUND FLOOR PLAN

with the Massachusetts Energy Code (used as a simple alternative to the complex lighting calculations required by ASHRAE 90-75).

B.1.4 Additional Assumption: Individual apartments were not modeled separately. Instead, the entire building was modeled, assuming a single interior zone and a separate exterior zone for each building exposure.

B.2 Retail Store

B.2.1 Summary Description of Selected Building

A. Name and Location:
Retail Store
Sears, Roebuck and Company
South Hills Mall
Poughkeepsie, New York

B. Form: One-story, rectangular "anchor" store, attached to a suburban enclosed mall shopping center.

C. Size: The gross floor area is 112,163 square feet, of which 75 percent is Retail/Administration and 25 percent is Receiving/Stock Rooms.

D. Construction: Structural steel column and beam system with steel roof joists. The roof is flat and consists of a metal deck, rigid insulation board, and built-up roofing. The perimeter walls consist of a 4" brick exterior, 2" air space, 8" concrete block interior with a finished surface of drywall over metal furring. The floor slab is concrete on grade.

E. Building Orientation and Floor Plan: See Figures B-2 through B-3.

B.2.2 Modifications

A. The building was modified by elmination of an attached Auto Center. This is justified by:

1) Current Sears practice incorporates the Auto Center into the basic envelope.

2) Auto Centers are in effect different use types, in that a high percentage of the space is industrial (garage).

3) Integral or attached Auto Centers are not typical of the generic building type.

B. A further simplification/modification involved interior sub-division. Since the arrangement of retail, storage, and administrative space varies widely in buildings of this type, and since specific sub-division is not essential, each zone was assigned a proportionate share of each of those three space types.

FIGURE B-2

RETAIL STORE EXTERIOR

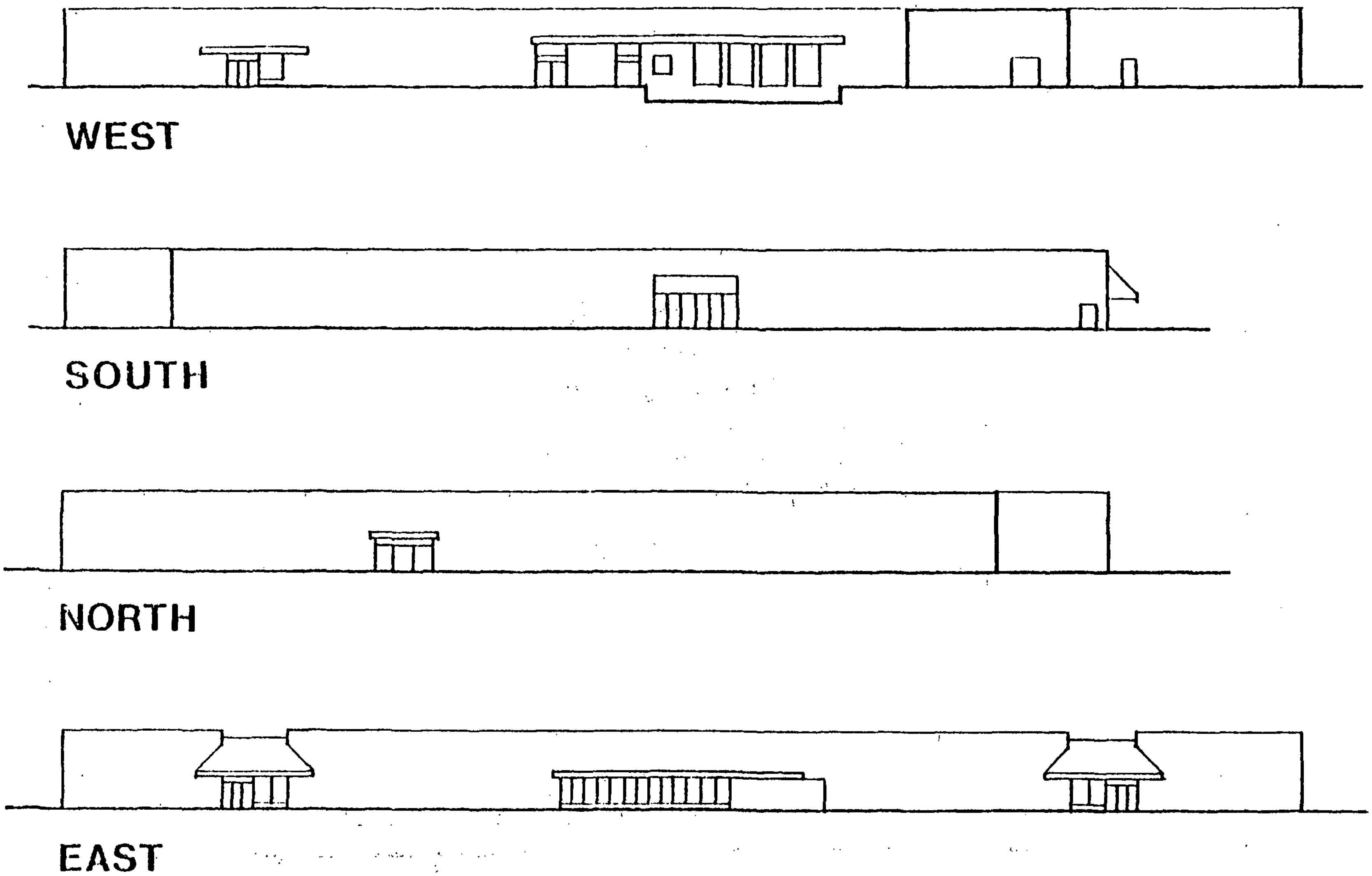
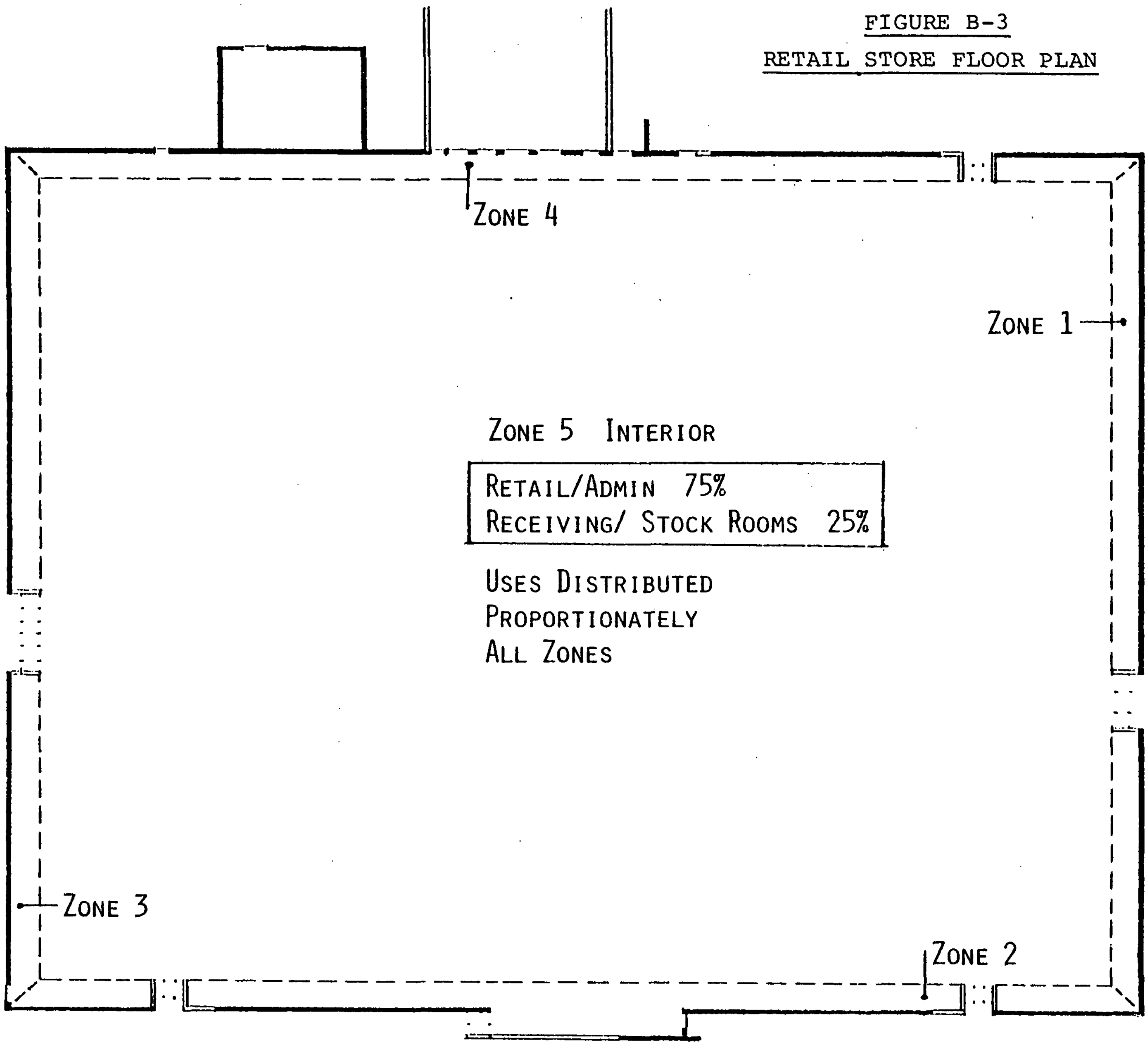


FIGURE B-3

RETAIL STORE FLOOR PLAN



B.2.3 ASHRAE 90-75 Compliance

The Study building was superior to the requirements of ASHRAE 90-75 in most respects. Three adjustments were made:

1) Roof insulation was increased to meet ASHRAE 90-75 standards.

2) The lighting level was reduced from 3.46 w/ft^2 to 3.0 w/ft^2 to meet the requirements of the Massachusetts Energy Code (used as a simple alternative to the complex lighting calculations required by ASHRAE 90-75).

3) Since HVAC systems were in effect redesigned for this project, because of new climates, the requirements of ASHRAE 90-75 were incorporated into HVAC systems and components.

B.3 Hospital

B.3.1 Summary Description of Selected Building

A. Name and Location:
Good Samaritan Hospital
Hataway Park and South Third Street
Lebanon, Pennsylvania

B. Form: Four floors with basement open to grade on one side, attached to an existing hospital unit.

C. Size: The gross floor area is 118,867 sq. ft. There are a total of 120 patient-care beds. The ground floor is open to grade on one side and contains Emergency, Radiology and Physical Therapy facilities. The first floor contains Administration, Snack Bar, Operating Suite, Laboratory, and Intensive Care facilities. Patient-care facilities are located on the second, third, and fourth floors.

D. Construction: Poured-in-place reinforced concrete column, beam and floor system. The roof is flat and consists of a concrete deck with insulating fill and built-up roof above. The perimeter walls consist of 4" brick exterior, 2" air space, 6" concrete block interior, with a finished surface of drywall over metal furring.

E. Building Orientation and Floor Plan: See Figures B-4 through B-5.

FIGURE B-4

HOSPITAL EXTERIOR

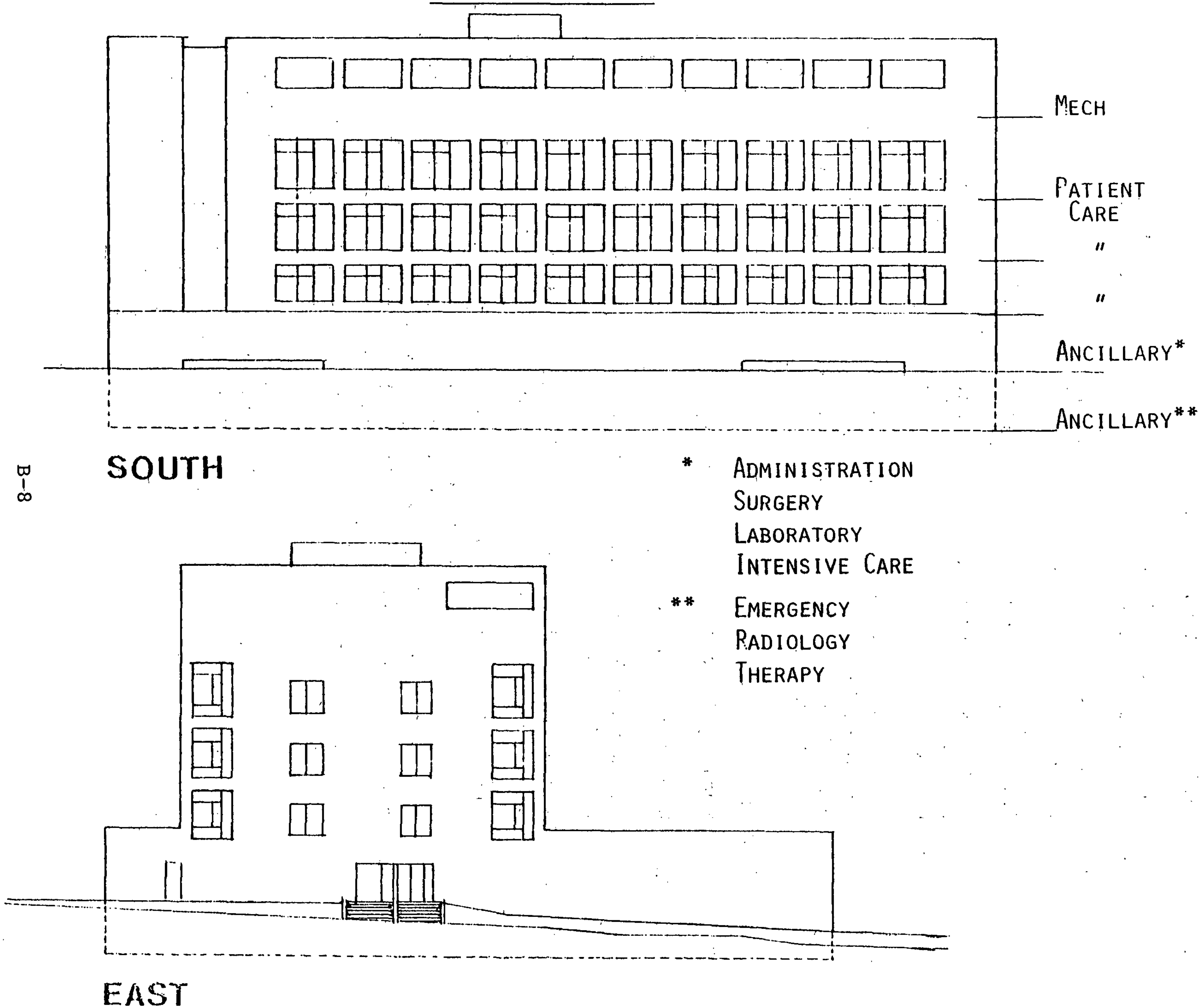
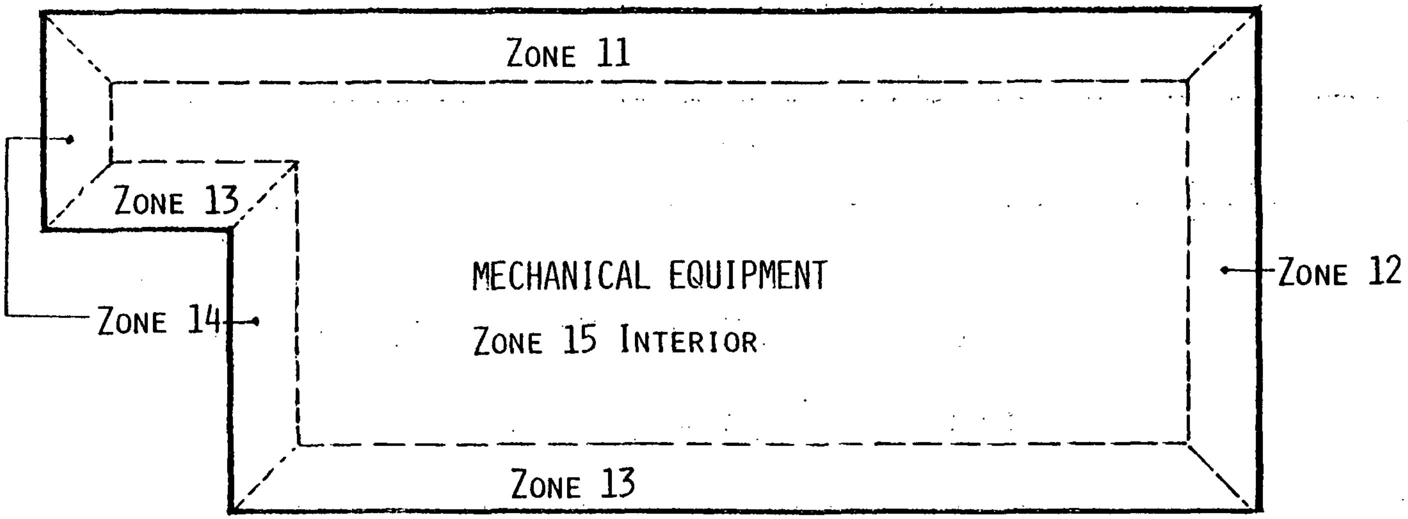
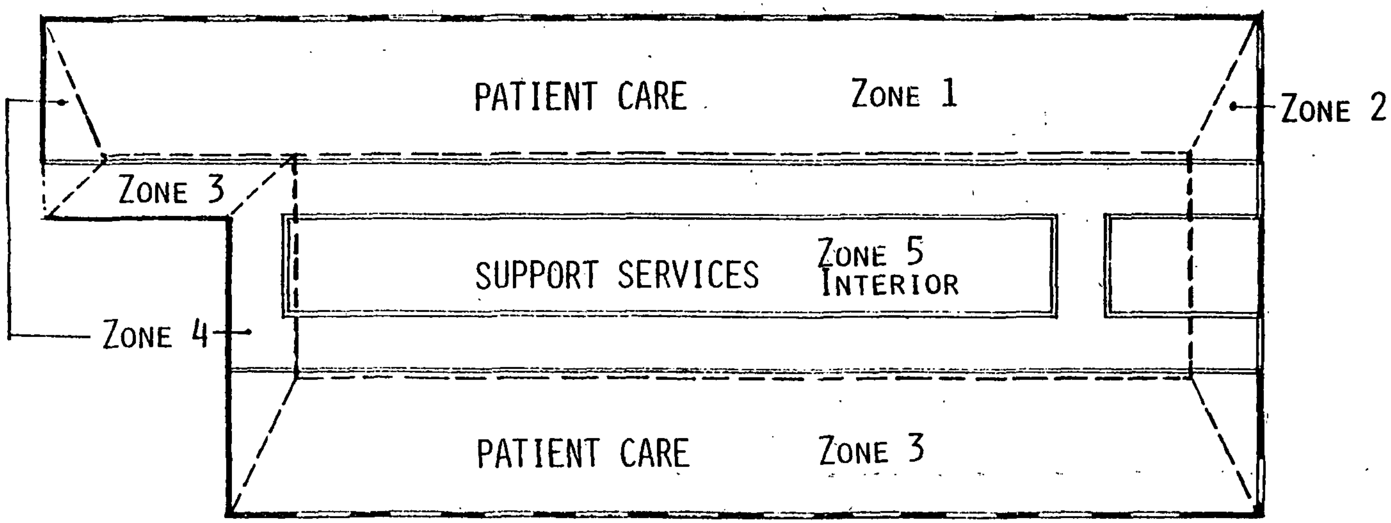


FIGURE B-5

HOSPITAL INTERIOR



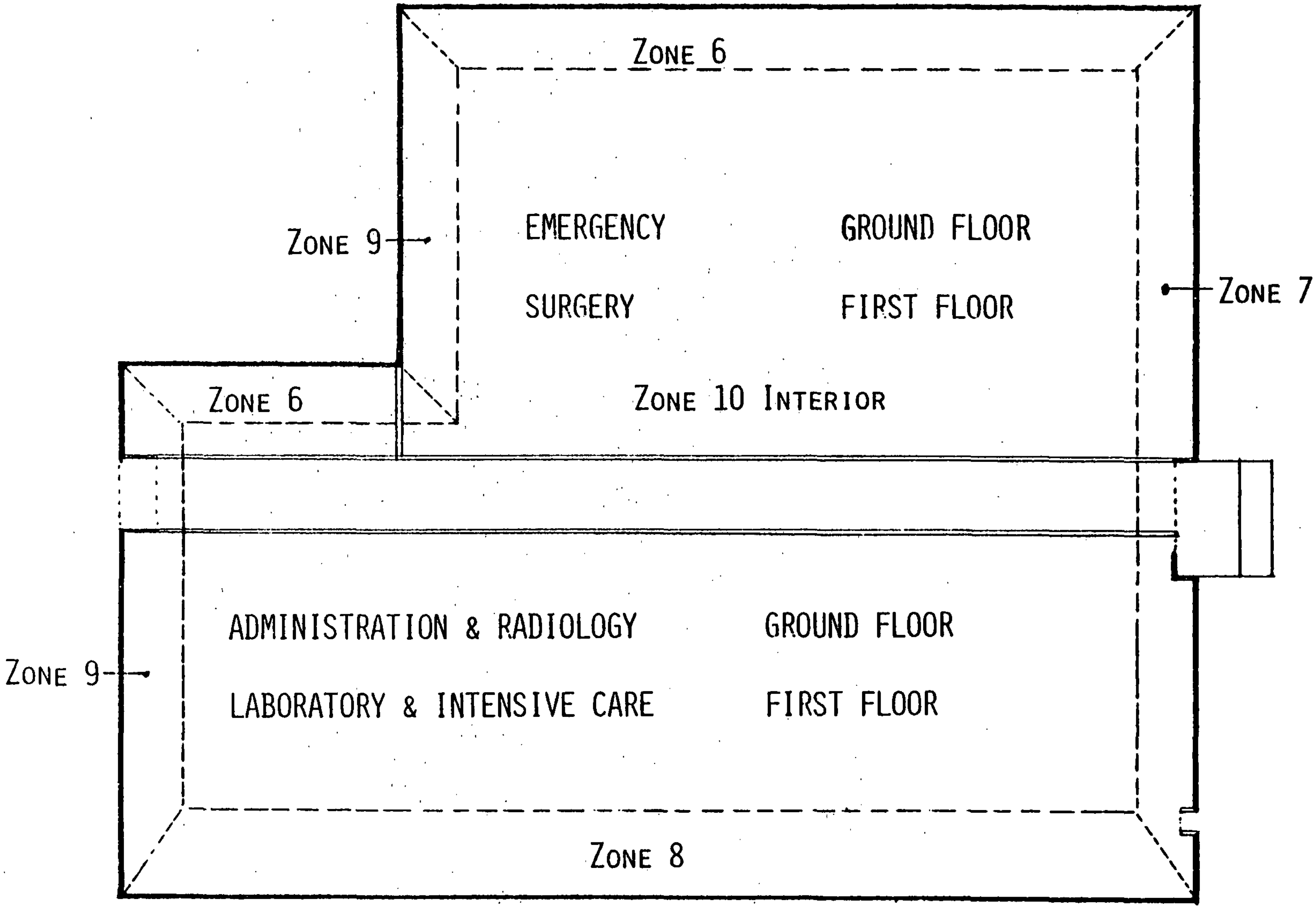
MECHANICAL PENTHOUSE PLAN



2nd, 3rd & 4th FLOOR PLANS

FIGURE B-5 (continued)

HOSPITAL INTERIOR



GROUND & FIRST FLOOR PLANS

B.3.2 Modifications

A. The building was modified by the elimination of the attached, older hospital facility. This is justified by the fact that the Ballinger addition could exist as an independent unit since it contains, in the proper portions, all the elements of a moderate sized suburban or rural hospital.

B. A further simplification/modification involved fenestration. The Ballinger window design included a section in the plane of the mail wall combined with a section angled back into the building so as to "afford" an exterior view to each patient in a 2-bed room. This window design was simplified/modified by the substitution of a window of equivalent area, in the plane of the main wall. This is justified by the fact that the original design is atypical and of no significance to this Study, as it was done solely to provide patient views from a particular arrangement of beds.

B.3.3 ASHRAE 90-75 Compliance

The Study building met the requirements of ASHRAE 90-75 in most respects. However, the following adjustments were made:

1) Roof installation was increased to meet ASHRAE 90-75 for all three locations.

2) The original and redesigned HVAC systems were revised to meet the requirements of ASHRAE 90-75.

APPENDIX C

AXCESS INPUTS

TABLE C-1

BUILDING DESIGN INPUTS: LOW-RISE APARTMENT BUILDING

- Building Size:

- Roof	10,248 ft^2	(952 M^2)
- Walls	8,442 ft^2	(784 M^2)
- Glass	1,704 ft^2	(158 M^2)
- Gross Floor Area	20,496 ft^2	(1904 M^2)

- Master Ceiling Height:

  8 ft (2.44 M)

- Average U-Factors

	(BTUH/^{o}F-ft^2)	kW_t/^{o}C-M^2
- Roof	0.050	0.284
- Walls	0.100	0.568
- Glass	0.750	4.26

- Maximum Occupancy:
  (see occupancy profile #4 attached)

  72

- Indoor Conditions:

  Summer: 78^{o}F (26^{o}C),50% relative humidity

  Winter: 72^{o}F, (22^{o}C), 5% relative humidity

TABLE C-2

BASE UTILITY LOADS: LOW-RISE APARTMENT BUILDING

LOAD	VALUE (kW)	PROFILE #
Interior Lighting and Recepticles	13	1
Exterior Lighting	5	---
Exhaust Fans	2	4
Cooking Equipment	39	2
Food Service Refrigeration	4	1
Individual Units - Domestic Hot Water Heating	42	3

TABLE C-3

APARTMENT BUILDING ENERGY USE PROFILE

(% of Base Utility Load)

PROFILE 1 - LIGHTG,APPLIANCES&REFRIGERAT

HR	SUN	MON	TUE	WED	THR	FRI	SAT	HOL	VAC
1	49	49	49	49	49	49	49	49	49
2	39	39	39	39	39	39	39	39	39
3	35	35	35	35	35	35	35	35	35
4	35	35	35	35	35	35	35	35	35
5	35	35	35	35	35	35	35	35	35
6	36	36	36	36	36	36	36	36	36
7	40	40	40	40	40	40	40	40	40
8	48	48	48	48	48	48	48	48	48
9	51	51	51	51	51	51	51	51	51
10	48	48	48	48	48	48	48	48	48
11	47	47	47	47	47	47	47	47	47
12	48	48	48	48	48	48	48	48	48
13	48	48	48	48	48	48	48	48	48
14	48	48	48	48	48	48	48	48	48
15	49	49	49	49	49	49	49	49	49
16	49	49	49	49	49	49	49	49	49
17	61	61	61	61	61	61	61	61	61
18	83	83	83	83	83	83	83	83	83
19	95	95	95	95	95	95	95	95	95
20	100	100	100	100	100	100	100	100	100
21	100	100	100	100	100	100	100	100	100
22	95	95	95	95	95	95	95	95	95
23	83	83	83	83	83	83	83	83	83
24	64	64	64	64	64	64	64	64	64

PROFILE 2 - RANGE OVEN

HR	SUN	MON	TUE	WED	THR	FRI	SAT	HOL	VAC
1	4	4	4	4	4	4	4	4	4
2	2	2	2	2	2	2	2	2	2
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	2	2	2	2	2	2	2	2	2
6	8	8	8	8	8	8	8	8	8
7	22	22	22	22	22	22	22	22	22
8	32	32	32	32	32	32	32	32	32
9	28	28	28	28	28	28	28	28	28
10	21	21	21	21	21	21	21	21	21
11	25	25	25	25	25	25	25	25	25
12	32	32	32	32	32	32	32	32	32
13	32	32	32	32	32	32	32	32	32
14	28	28	28	28	28	28	28	28	28
15	33	33	33	33	33	33	33	33	33
16	51	51	51	51	51	51	51	51	51
17	79	79	79	79	79	79	79	79	79
18	100	100	100	100	100	100	100	100	100
19	59	59	59	59	59	59	59	59	59
20	25	25	25	25	25	25	25	25	25
21	13	13	13	13	13	13	13	13	13
22	9	9	9	9	9	9	9	9	9
23	9	9	9	9	9	9	9	9	9
24	8	8	8	8	8	8	8	8	8

TABLE C-3 (continued)

APARTMENT BUILDING ENERGY USE PROFILE

(% of Base Utility Load)

PROFILE 3 - DOMESTIC HOT WATER HTG

HR	SUN	MON	TUE	WED	THR	FRI	SAT	HOL	VAC
1	5	5	5	5	5	5	5	5	5
2	5	5	5	5	5	5	5	5	5
3	5	5	5	5	5	5	5	5	5
4	5	5	5	5	5	5	5	5	5
5	5	5	5	5	5	5	5	5	5
6	20	30	30	30	30	30	25	20	20
7	45	40	40	40	40	40	45	45	45
8	45	55	55	55	55	55	45	45	45
9	45	55	55	55	55	55	50	45	45
10	35	45	45	45	45	45	50	35	35
11	40	40	40	40	40	40	45	40	40
12	40	45	45	45	45	45	40	40	40
13	40	45	45	45	45	45	40	40	40
14	30	35	35	35	35	35	35	30	30
15	20	25	25	25	25	25	20	20	20
16	25	35	35	35	35	35	30	25	25
17	40	50	50	50	50	50	45	40	40
18	45	65	65	65	65	65	50	45	45
19	45	60	60	60	60	60	40	45	45
20	40	50	50	50	50	50	40	40	40
21	40	40	40	40	40	40	40	40	40
22	30	30	30	30	30	30	35	30	30
23	20	25	25	25	25	25	25	20	20
24	15	15	15	15	15	15	15	15	15

PROFILE 4 - OCCUPANCY&EXHAUST FANS

HR	SUN	MON	TUE	WED	THR	FRI	SAT	HOL	VAC
1	95	95	95	95	95	95	95	95	95
2	95	95	95	95	95	95	95	95	95
3	95	95	95	95	95	95	95	95	95
4	95	95	95	95	95	95	95	95	95
5	95	95	95	95	95	95	95	95	95
6	95	95	95	95	95	95	95	95	95
7	90	80	80	80	80	80	95	90	90
8	90	80	80	80	80	80	90	90	90
9	80	75	75	75	75	75	80	80	80
10	70	65	65	65	65	65	80	70	70
11	70	65	65	65	65	65	75	70	70
12	70	65	65	65	65	65	70	70	70
13	70	65	65	65	65	65	70	70	70
14	70	65	65	65	65	65	70	70	70
15	70	65	65	65	65	65	70	70	70
16	80	80	80	80	80	80	75	80	80
17	80	80	80	80	80	80	80	80	80
18	80	85	85	85	85	85	90	80	80
19	95	85	85	85	85	85	95	95	95
20	95	85	85	85	85	85	95	95	95
21	95	95	95	95	95	95	95	95	95
22	95	95	95	95	95	95	95	95	95
23	95	95	95	95	95	95	95	95	95
24	95	95	95	95	95	95	95	95	95

TABLE C-4

BUILDING DESIGN INPUTS: RETAIL STORE

• Building Size:		
- Roof	112,163 ft^2 (10,420 M^2)	
- Walls (not including glass)	27,063 ft^2 (2,514 M^2)	
- Glass	1,801 ft^2 (167 M^2)	
- Gross Floor Area	112,163 ft^2 (10,420 M^2)	
• Master Ceiling Height:	10 ft (3.05 M)	
• Average U-Factors	BTUH/^{o}F-ft^2	kW$_t$/^{o}C-M^2
- Roof	0.100	0.568
- Walls	0.214	1.216
- Glass	0.600	3.410
• Maximum Occupancy:	(see occupancy profile #2 attached)	
• Indoor Conditions:		
- Summer	78^{o}F (26^{o}C), 50% Relative Humidity	
- Winter	72^{o}F (22^{o}C), 5% Relative Humidity	
• Infiltration, Air Changes Per Hour		
- Perimeter Zone, West	4.0	
- All Other Perimeter Zones	1.5	
- Interior Zone	0	

NOTE: Economizer cycle assumed.

TABLE C-5

BASE UTILITY LOADS: RETAIL STORE

LOAD	VALUE (kW)	PROFILE #
Interior Lighting and Recepticles	281	1
Exterior Lighting	22	0
Exhaust Fans	6	4
Cooking Equipment	97	5
Food Service Refrigeration	12	6
Individual Units - Domestic Hot Water Heating	60	7
Business Machines	56	3
Cooking Exhaust Fans	12	5

TABLE C-6

RETAIL STORE ENERGY USE PROFILES

(% of Base Utility Load)

PROFILE 1 - INTERIOR LIGHTING

HR	SUN	MON	TUE	WED	THR	FRI	SAT	HOL	VAC
1	5	5	5	5	5	5	5	5	5
2	5	5	5	5	5	5	5	5	5
3	5	5	5	5	5	5	5	5	5
4	5	5	5	5	5	5	5	5	5
5	5	5	5	5	5	5	5	5	5
6	5	5	5	5	5	5	5	5	5
7	5	20	20	20	20	20	20	5	5
8	10	40	40	40	40	40	40	10	10
9	10	90	90	90	90	90	90	10	10
10	40	90	90	90	90	90	90	40	40
11	40	90	90	90	90	90	90	40	40
12	60	90	90	90	90	90	90	60	60
13	60	90	90	90	90	90	90	60	60
14	60	90	90	90	90	90	90	60	60
15	60	90	90	90	90	90	90	60	60
16	60	90	90	90	90	90	90	60	60
17	60	90	90	90	90	90	90	60	60
18	40	90	90	90	90	90	90	40	40
19	20	60	60	60	60	60	60	20	20
20	5	60	60	60	60	60	60	5	5
21	5	50	50	50	50	50	50	5	5
22	5	20	20	20	20	20	20	5	5
23	5	5	5	5	5	5	5	5	5
24	5	5	5	5	5	5	5	5	5

PROFILE 2 - PEOPLE

HR	SUN	MON	TUE	WED	THR	FRI	SAT	HOL	VAC
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0
8	0	20	20	20	20	20	20	0	0
9	10	50	50	50	50	50	50	10	10
10	20	50	50	50	50	50	50	20	20
11	20	75	75	75	75	75	75	20	20
12	40	80	80	80	80	80	80	40	40
13	40	80	80	80	80	80	80	40	40
14	40	80	80	80	80	80	80	40	40
15	40	80	80	80	80	80	80	40	40
16	40	80	80	80	80	80	80	40	40
17	40	50	50	50	50	50	50	40	40
18	20	50	50	50	50	50	50	20	20
19	10	50	50	50	50	50	50	10	10
20	0	30	30	30	30	30	30	0	0
21	0	30	30	30	30	30	30	0	0
22	0	10	10	10	10	10	10	0	0
23	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0

TABLE C-6 (continued)

RETAIL STORE ENERGY USE PROFILES

(% of Base Utility Load)

PROFILE 3 - BUSINESS MACHINES

HR	SUN	MON	TUE	WED	THR	FRI	SAT	HOL	VAC
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	60	60	60	60	60	60	60	60	60
6	60	60	60	60	60	60	60	60	60
7	60	60	60	60	60	60	60	60	60
8	60	100	100	100	100	100	100	60	60
9	60	100	100	100	100	100	100	60	60
10	60	100	100	100	100	100	100	60	60
11	60	100	100	100	100	100	100	60	60
12	60	100	100	100	100	100	100	60	60
13	60	100	100	100	100	100	100	60	60
14	60	100	100	100	100	100	100	60	60
15	60	100	100	100	100	100	100	60	60
16	60	100	100	100	100	100	100	60	60
17	60	100	100	100	100	100	100	60	60
18	60	60	60	60	60	60	60	60	60
19	60	60	60	60	60	60	60	60	60
20	60	60	60	60	60	60	60	60	60
21	60	60	60	60	60	60	60	60	60
22	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0

PROFILE 4 - EXHAUST FANS

HR	SUN	MON	TUE	WED	THR	FRI	SAT	HOL	VAC
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0
8	0	100	100	100	100	100	100	0	0
9	100	100	100	100	100	100	100	100	100
10	100	100	100	100	100	100	100	100	100
11	100	100	100	100	100	100	100	100	100
12	100	100	100	100	100	100	100	100	100
13	100	100	100	100	100	100	100	100	100
14	100	100	100	100	100	100	100	100	100
15	100	100	100	100	100	100	100	100	100
16	100	100	100	100	100	100	100	100	100
17	100	100	100	100	100	100	100	100	100
18	100	100	100	100	100	100	100	100	100
19	0	100	100	100	100	100	100	0	0
20	0	100	100	100	100	100	100	0	0
21	0	100	100	100	100	100	100	0	0
22	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0

TABLE C-6 (continued)

RETAIL STORE ENERGY USE PROFILES

(% of Base Utility Load)

PROFILE 5 - COOKING EQUIPMENT&EXHAUSTFAN

HR	SUN	MON	TUE	WED	THR	FRI	SAT	HOL	VAC
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0
8	0	50	50	50	50	50	50	0	0
9	0	50	50	50	50	50	50	0	0
10	30	100	100	100	100	100	100	30	30
11	60	100	100	100	100	100	100	60	60
12	60	100	100	100	100	100	100	60	60
13	60	100	100	100	100	100	100	60	60
14	60	100	100	100	100	100	100	60	60
15	60	100	100	100	100	100	100	60	60
16	60	100	100	100	100	100	100	60	60
17	60	100	100	100	100	100	100	60	60
18	30	100	100	100	100	100	100	30	30
19	0	50	50	50	50	50	50	0	0
20	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0

PROFILE 6 - FOOD SERVICE REFRIGERATION

HR	SUN	MON	TUE	WED	THR	FRI	SAT	HOL	VAC
1	100	100	100	100	100	100	100	100	100
2	100	100	100	100	100	100	100	100	100
3	100	100	100	100	100	100	100	100	100
4	100	100	100	100	100	100	100	100	100
5	100	100	100	100	100	100	100	100	100
6	100	100	100	100	100	100	100	100	100
7	100	100	100	100	100	100	100	100	100
8	100	100	100	100	100	100	100	100	100
9	100	100	100	100	100	100	100	100	100
10	100	100	100	100	100	100	100	100	100
11	100	100	100	100	100	100	100	100	100
12	100	100	100	100	100	100	100	100	100
13	100	100	100	100	100	100	100	100	100
14	100	100	100	100	100	100	100	100	100
15	100	100	100	100	100	100	100	100	100
16	100	100	100	100	100	100	100	100	100
17	100	100	100	100	100	100	100	100	100
18	100	100	100	100	100	100	100	100	100
19	100	100	100	100	100	100	100	100	100
20	100	100	100	100	100	100	100	100	100
21	100	100	100	100	100	100	100	100	100
22	100	100	100	100	100	100	100	100	100
23	100	100	100	100	100	100	100	100	100
24	100	100	100	100	100	100	100	100	100

TABLE C-6 (continued)

RETAIL STORE ENERGY USE PROFILES

(% of Base Utility Load)

PROFILE 7 - DOMESTIC HW HEATER

HR	SUN	MON	TUE	WED	THR	FRI	SAT	HOL	VAC
1	5	5	5	5	5	5	5	5	5
2	5	5	5	5	5	5	5	5	5
3	5	5	5	5	5	5	5	5	5
4	5	5	5	5	5	5	5	5	5
5	5	10	10	10	10	10	10	5	5
6	5	10	10	10	10	10	10	5	5
7	5	20	20	20	20	20	20	5	5
8	20	20	20	20	20	20	20	20	20
9	20	30	30	30	30	30	30	20	20
10	30	40	40	40	40	40	40	30	30
11	30	60	60	60	60	60	60	30	30
12	30	60	60	60	60	60	60	30	30
13	30	60	60	60	60	60	60	30	30
14	30	60	60	60	60	60	60	30	30
15	30	40	40	40	40	40	40	30	30
16	30	40	40	40	40	40	40	30	30
17	30	40	40	40	40	40	40	30	30
18	30	30	30	30	30	30	30	30	30
19	20	30	30	30	30	30	30	20	20
20	20	20	20	20	20	20	20	20	20
21	10	20	20	20	20	20	20	10	10
22	10	20	20	20	20	20	20	10	10
23	5	5	5	5	5	5	5	5	5
24	5	5	5	5	5	5	5	5	5

TABLE C-7

BUILDING DESIGN INPUTS: HOSPITAL

• Building Size:		
- Roof	29,563 ft^2	(2,746 M^2)
- Walls (not including glass)	39,228 ft^2	(3,644 M^2)
- Glass	5,040 ft^2	(468 M^2)
- Gross Floor Area	118,867 ft^2	(11,043 M^2)
• Master Ceiling Height	9 ft (2.74 M)	
• Average U-Factors	BTH/^{O}F-ft^2	kW_t/^{O}C-M^2
- Roof	0.077	0.438
- Walls	0.188	1.068
- Glass	0.600	3.410
• Maximum Occupancy:	(see occupancy profile #2 attached)	
• Indoor Conditions:		
- Summer	72^{O}F (24^{O}C), 50% Relative Humidity	
- Winter	75^{O}F (24^{O}C), 50% Relative Humidity	
• Infiltration, Air Changes Per Hour		
- Zones 6 and 7	1.5	
- Zones 2 and 9	0.8	
- Zone 8	0.5	
- Zones 1 and 3	0.3	
- All Other Zones	0.0	

TABLE C-8

BASE UTILITY LOADS: HOSPITAL

LOAD	VALUE (kW)	PROFILE #
Interior Lighting and Recepticles	309	1
Exterior Lighting	10	0
Exhaust Fans	16	6
Cooking Equipment	46	5
Food Service Refrigeration	3	6
Individual Units - Domestic Hot Water Heating	293	3

TABLE C-9

HOSPITAL ENERGY USE PROFILES

(% of Base Utility Load)

PROFILE 1 - INTERIOR LIGHTING

HR	SUN	MON	TUE	WED	THR	FRI	SAT	HOL	VAC
1	50	60	60	60	60	60	50	50	50
2	50	60	60	60	60	60	50	50	50
3	50	60	60	60	60	60	50	50	50
4	50	60	60	60	60	60	50	50	50
5	50	60	60	60	60	60	50	50	50
6	50	75	75	75	75	75	50	50	50
7	75	80	80	80	80	80	75	75	75
8	75	90	90	90	90	90	75	75	75
9	75	90	90	90	90	90	75	75	75
10	75	90	90	90	90	90	75	75	75
11	75	90	90	90	90	90	75	75	75
12	75	90	90	90	90	90	75	75	75
13	75	90	90	90	90	90	75	75	75
14	75	90	90	90	90	90	75	75	75
15	75	90	90	90	90	90	75	75	75
16	75	90	90	90	90	90	75	75	75
17	75	90	90	90	90	90	75	75	75
18	75	90	90	90	90	90	75	75	75
19	75	90	90	90	90	90	75	75	75
20	75	90	90	90	90	90	75	75	75
21	50	75	75	75	75	75	50	50	50
22	50	60	60	60	60	60	50	50	50
23	50	60	60	60	60	60	50	50	50
24	50	60	60	60	60	60	50	50	50

PROFILE 2 - OCCUPANCY

HR	SUN	MON	TUE	WED	THR	FRI	SAT	HOL	VAC
1	60	70	70	70	70	70	60	60	60
2	60	70	70	70	70	70	60	60	60
3	60	70	70	70	70	70	60	60	60
4	60	70	70	70	70	70	60	60	60
5	60	70	70	70	70	70	60	60	60
6	70	75	75	75	75	75	60	70	70
7	80	95	95	95	95	95	70	80	80
8	80	95	95	95	95	95	80	80	80
9	80	95	95	95	95	95	80	80	80
10	80	95	95	95	95	95	80	80	80
11	80	95	95	95	95	95	80	80	80
12	80	95	95	95	95	95	80	80	80
13	80	95	95	95	95	95	80	80	80
14	80	95	95	95	95	95	80	80	80
15	80	95	95	95	95	95	80	80	80
16	80	95	95	95	95	95	80	80	80
17	80	95	95	95	95	95	80	80	80
18	80	95	95	95	95	95	80	80	80
19	80	95	95	95	95	95	80	80	80
20	80	95	95	95	95	95	80	80	80
21	70	75	75	75	75	75	70	70	70
22	60	70	70	70	70	70	60	60	60
23	60	70	70	70	70	70	60	60	60
24	60	70	70	70	70	70	60	60	60

TABLE C-9 (continued)

HOSPITAL ENERGY USE PROFILES

(% of Base Utility Load)

PROFILE 3 - DOMESTIC HOT WATER HTG

HR	SUN	MON	TUE	WED	THR	FRI	SAT	HOL	VAC
1	10	10	10	10	10	10	10	10	10
2	10	10	10	10	10	10	10	10	10
3	10	10	10	10	10	10	10	10	10
4	12	15	15	15	15	15	12	12	12
5	15	15	15	15	15	15	15	15	15
6	30	30	30	30	30	30	40	30	30
7	45	45	45	45	45	45	50	45	45
8	50	70	70	70	70	70	60	50	50
9	60	65	65	65	65	65	65	60	60
10	60	50	50	50	50	50	55	60	60
11	55	65	65	65	65	65	60	55	55
12	57	70	70	70	70	70	60	57	57
13	65	75	75	75	75	75	70	65	65
14	70	70	70	70	70	70	65	70	70
15	60	60	60	60	60	60	55	60	60
16	40	50	50	50	50	50	40	40	40
17	40	50	50	50	50	50	42	40	40
18	50	60	60	60	60	60	45	50	50
19	50	50	50	50	50	50	55	50	50
20	35	40	40	40	40	40	35	35	35
21	25	25	25	25	25	25	20	25	25
22	15	15	15	15	15	15	10	15	15
23	10	15	15	15	15	15	5	10	10
24	5	15	15	15	15	15	5	5	5

PROFILE 4 - VERTICAL TRANSPORTATION

HR	SUN	MON	TUE	WED	THR	FRI	SAT	HOL	VAC
1	15	15	15	15	15	15	15	15	15
2	15	15	15	15	15	15	15	15	15
3	15	15	15	15	15	15	15	15	15
4	15	15	15	15	15	15	15	15	15
5	15	15	15	15	15	15	15	15	15
6	25	25	25	25	25	25	25	25	25
7	35	45	45	45	45	45	40	35	35
8	45	65	65	65	65	65	50	45	45
9	50	60	60	60	60	60	60	50	50
10	55	75	75	75	75	75	70	55	55
11	60	80	80	80	80	80	65	60	60
12	60	75	75	75	75	75	65	60	60
13	60	75	75	75	75	75	65	60	60
14	60	80	80	80	80	80	70	60	60
15	65	85	85	85	85	85	75	65	65
16	60	90	90	90	90	90	70	60	60
17	60	85	85	85	85	85	65	60	60
18	60	75	75	75	75	75	65	60	60
19	55	60	60	60	60	60	60	55	55
20	50	60	60	60	60	60	55	50	50
21	40	35	35	35	35	35	40	40	40
22	30	30	30	30	30	30	30	30	30
23	25	30	30	30	30	30	25	25	25
24	25	30	30	30	30	30	30	25	25

TABLE C-9 (continued)

HOSPITAL ENERGY USE PROFILES

(% of Base Utility Load)

PROFILE 5 - COOKING FOOD PREP&SANIT EQPT

HR	SUN	MON	TUE	WED	THR	FRI	SAT	HOL	VAC
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	10	10	10	10	10	10	10	10	10
6	40	40	40	40	40	40	40	40	40
7	70	70	70	70	70	70	70	70	70
8	70	70	70	70	70	70	70	70	70
9	70	70	70	70	70	70	70	70	70
10	50	50	50	50	50	50	50	50	50
11	70	80	80	80	80	80	70	70	70
12	70	80	80	80	80	80	70	70	70
13	70	80	80	80	80	80	70	70	70
14	60	60	60	60	60	60	60	60	60
15	60	60	60	60	60	60	60	60	60
16	40	60	60	60	60	60	60	60	60
17	40	60	60	60	60	60	40	40	40
18	50	50	50	50	50	50	50	40	40
19	10	10	10	10	10	10	10	50	50
20	0	0	0	0	0	0	0	10	10
21	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0

PROFILE 6 - EXHAUST FANS&FOOD REFRIGERAT

HR	SUN	MON	TUE	WED	THR	FRI	SAT	HOL	VAC
1	100	100	100	100	100	100	100	100	100
2	100	100	100	100	100	100	100	100	100
3	100	100	100	100	100	100	100	100	100
4	100	100	100	100	100	100	100	100	100
5	100	100	100	100	100	100	100	100	100
6	100	100	100	100	100	100	100	100	100
7	100	100	100	100	100	100	100	100	100
8	100	100	100	100	100	100	100	100	100
9	100	100	100	100	100	100	100	100	100
10	100	100	100	100	100	100	100	100	100
11	100	100	100	100	100	100	100	100	100
12	100	100	100	100	100	100	100	100	100
13	100	100	100	100	100	100	100	100	100
14	100	100	100	100	100	100	100	100	100
15	100	100	100	100	100	100	100	100	100
16	100	100	100	100	100	100	100	100	100
17	100	100	100	100	100	100	100	100	100
18	100	100	100	100	100	100	100	100	100
19	100	100	100	100	100	100	100	100	100
20	100	100	100	100	100	100	100	100	100
21	100	100	100	100	100	100	100	100	100
22	100	100	100	100	100	100	100	100	100
23	100	100	100	100	100	100	100	100	100
24	100	100	100	100	100	100	100	100	100

TABLE C-9 (continued)

HOSPITAL ENERGY USE PROFILES

(% of Base Utility Load)

PROFILE 7 - PROCESS EQUIPMENT

HR	SUN	MON	TUE	WED	THR	FRI	SAT	HOL	VAC
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0
8	70	70	70	70	70	70	70	70	70
9	70	70	70	70	70	70	70	70	70
10	70	70	70	70	70	70	70	70	70
11	70	70	70	70	70	70	70	70	70
12	70	70	70	70	70	70	70	70	70
13	70	70	70	70	70	70	70	70	70
14	70	70	70	70	70	70	70	70	70
15	70	70	70	70	70	70	70	70	70
16	70	70	70	70	70	70	70	70	70
17	70	70	70	70	70	70	70	70	70
18	70	70	70	70	70	70	70	70	70
19	70	70	70	70	70	70	70	70	70
20	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0

APPENDIX D

END-USE LOAD PROFILES

FIGURE D-1

TYPICAL HOURLY LOAD PROFILE

BUILDING: Low-Rise Apartment
LOCATION: Washington, D.C.
SEASON: Winter

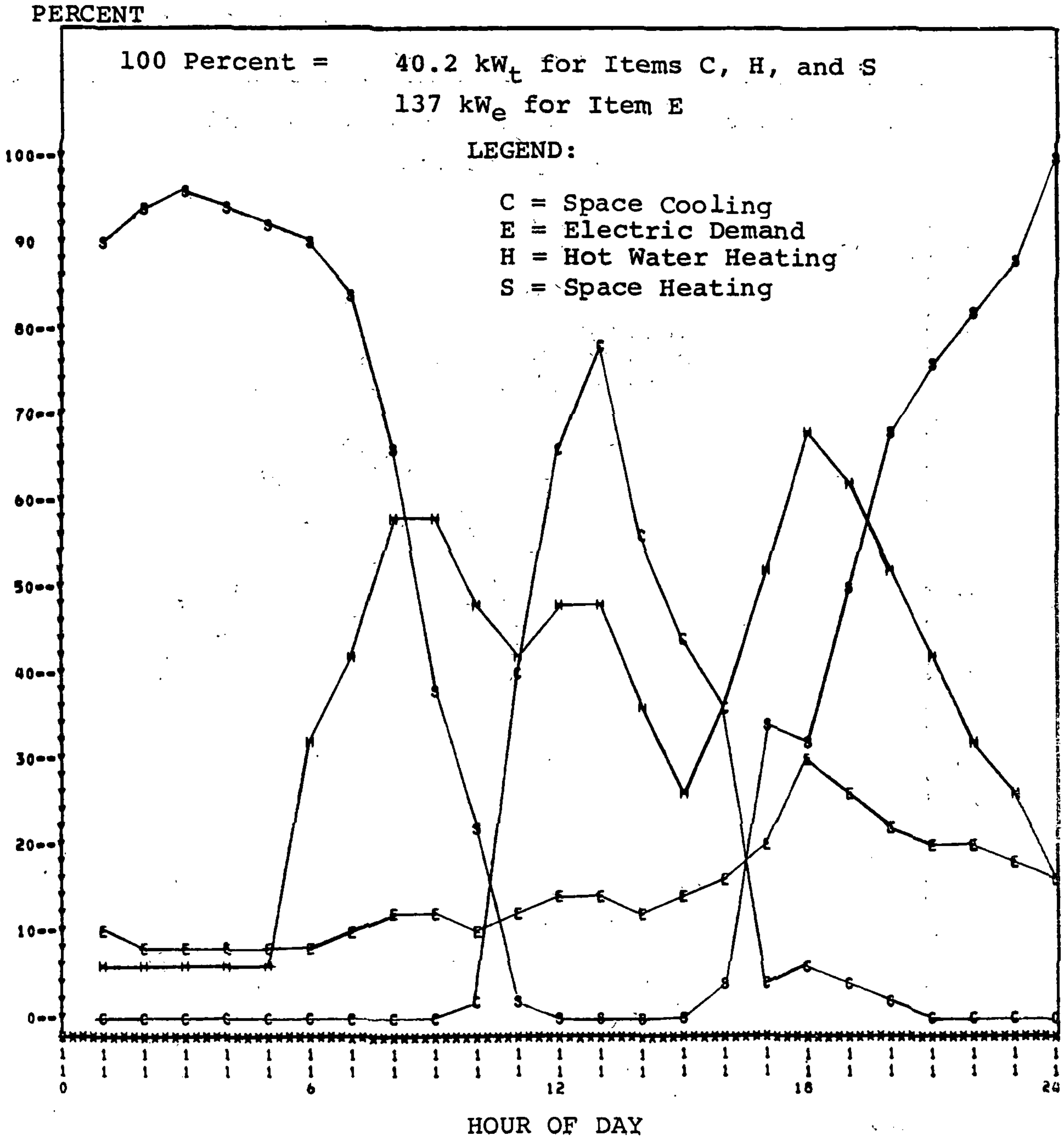


FIGURE D-2

TYPICAL HOURLY LOAD PROFILE

BUILDING: Low-Rise Apartment
LOCATION: Washington, D.C.
SEASON: Summer

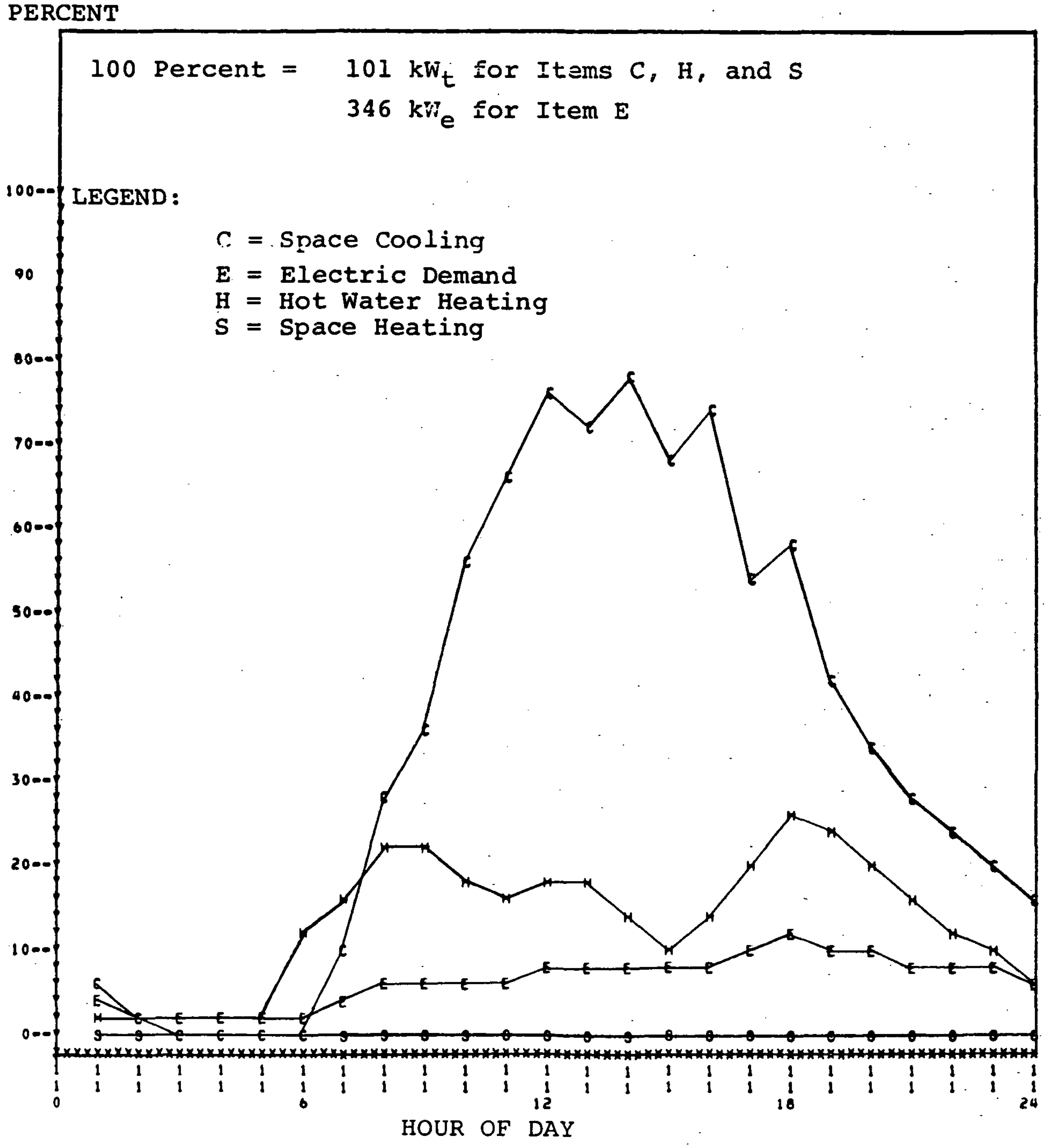


FIGURE D-3

TYPICAL HOURLY LOAD PROFILE

BUILDING: Low-Rise Apartment
LOCATION: Chicago, Illinois
SEASON: Winter

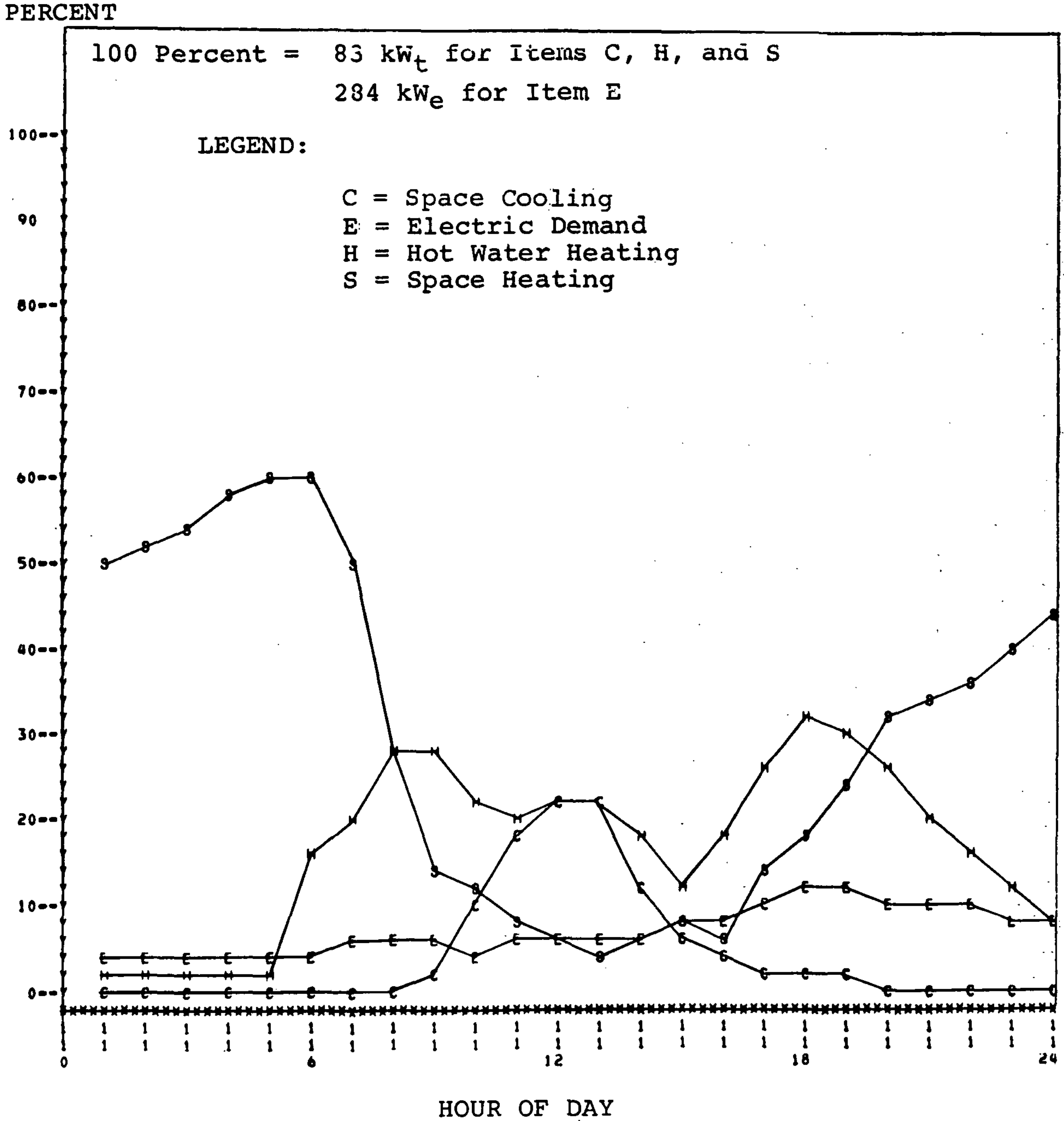


FIGURE D-4

TYPICAL HOURLY LOAD PROFILE

BUILDING: Low Rise Apartment
LOCATION: Chicago, Illinois
SEASON: Summer

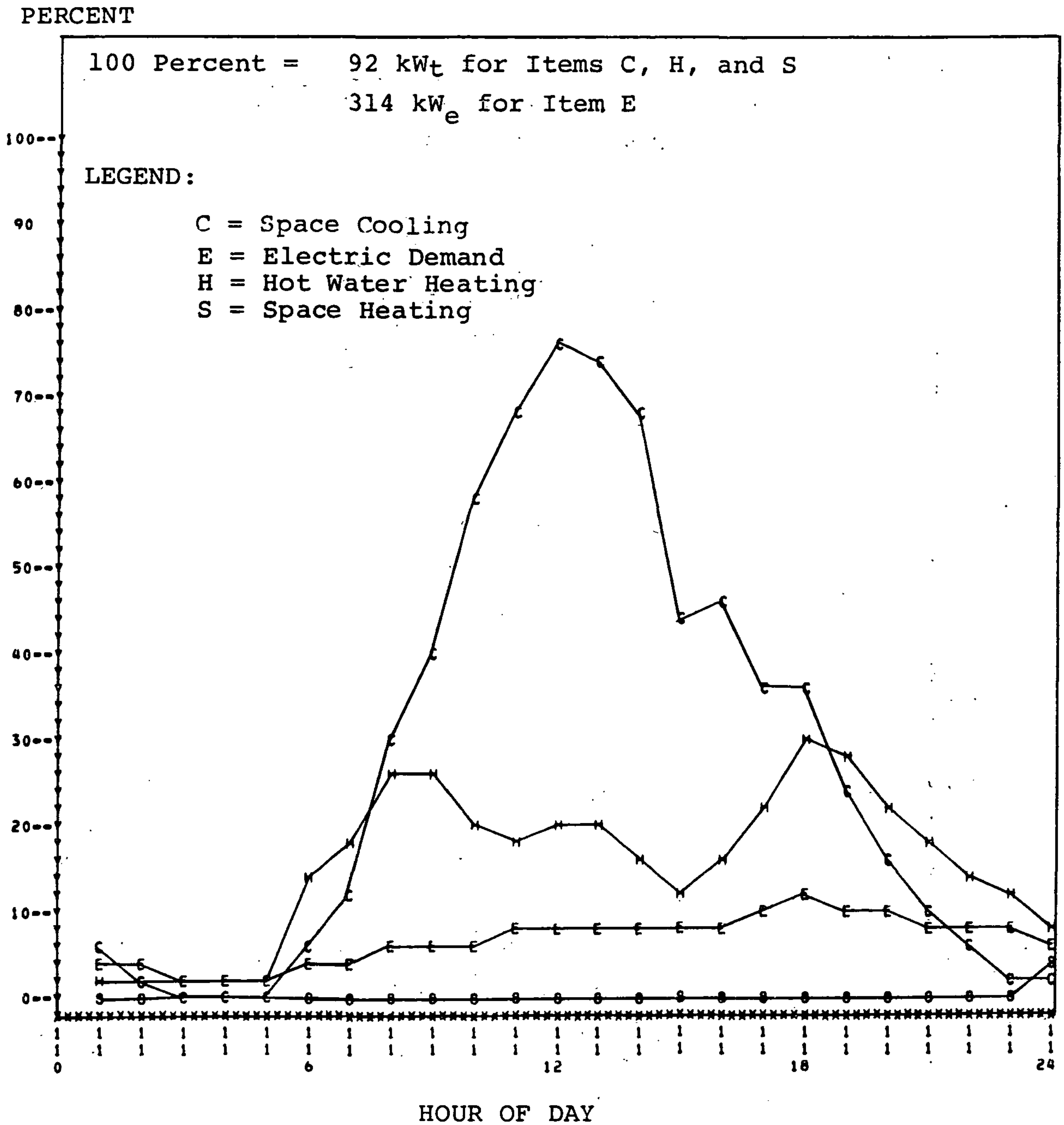


FIGURE D-5

TYPICAL HOURLY LOAD PROFILE

BUILDING: Low-Rise Apartment
LOCATION: Dallas, Texas
SEASON: Winter

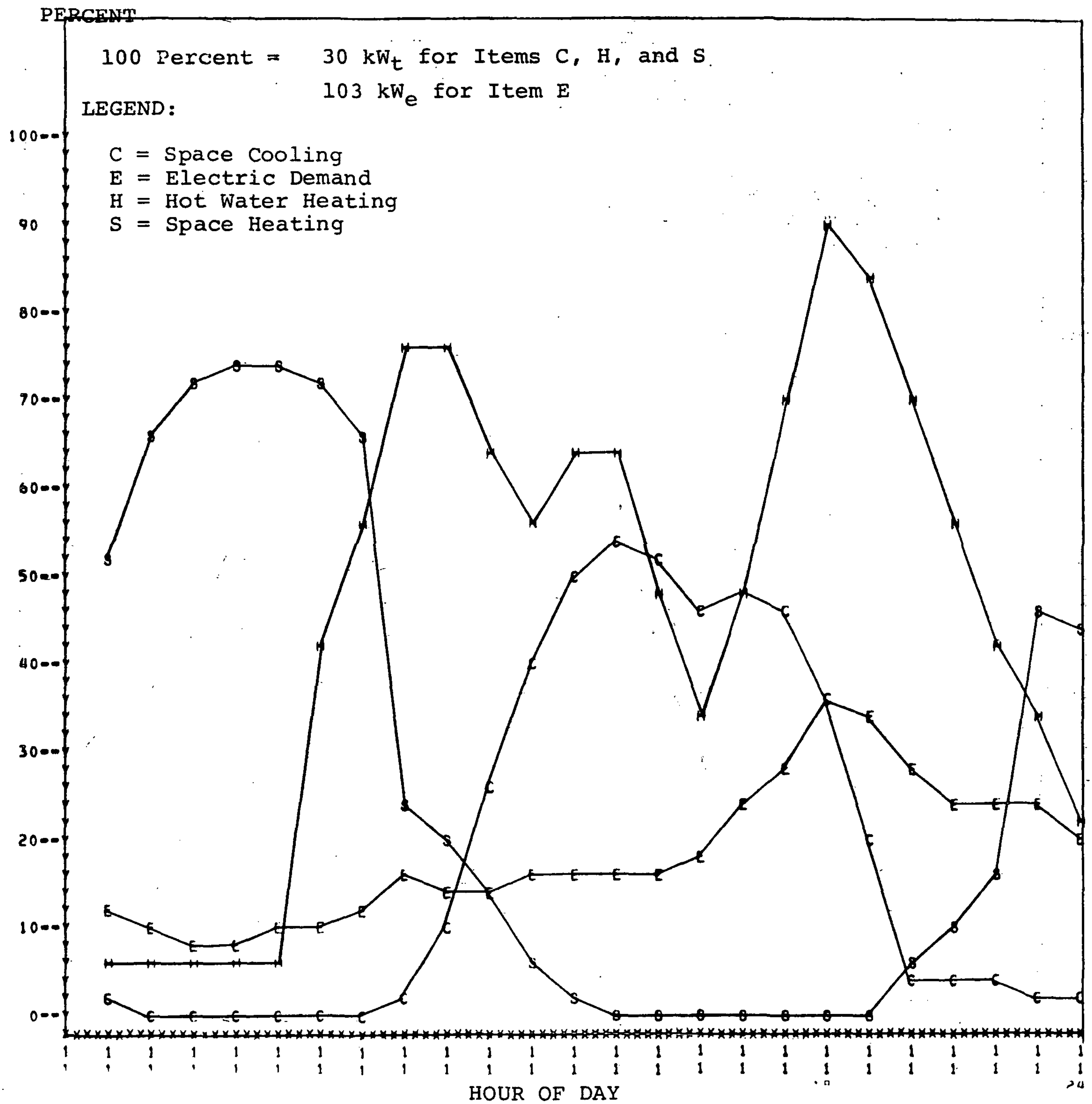


FIGURE D-6

TYPICAL HOURLY LOAD PROFILE

BUILDING: Low-Rise Apartment
LOCATION: Dallas, Texas
SEASON: Summer

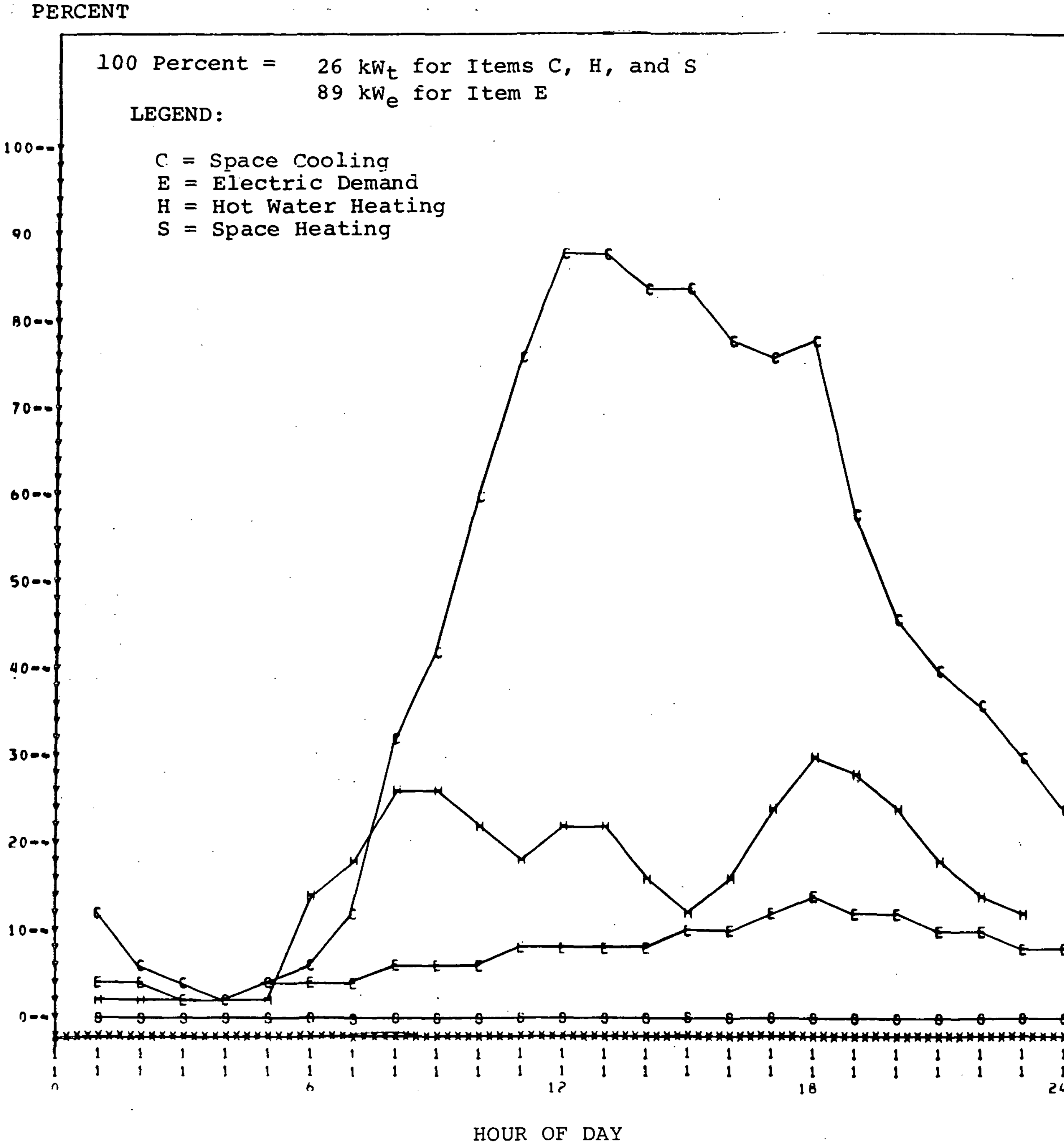


FIGURE D-7

TYPICAL HOURLY LOAD PROFILE

BUILDING: Retail Store
LOCATION: Washington, D.C.
SEASON: Winter

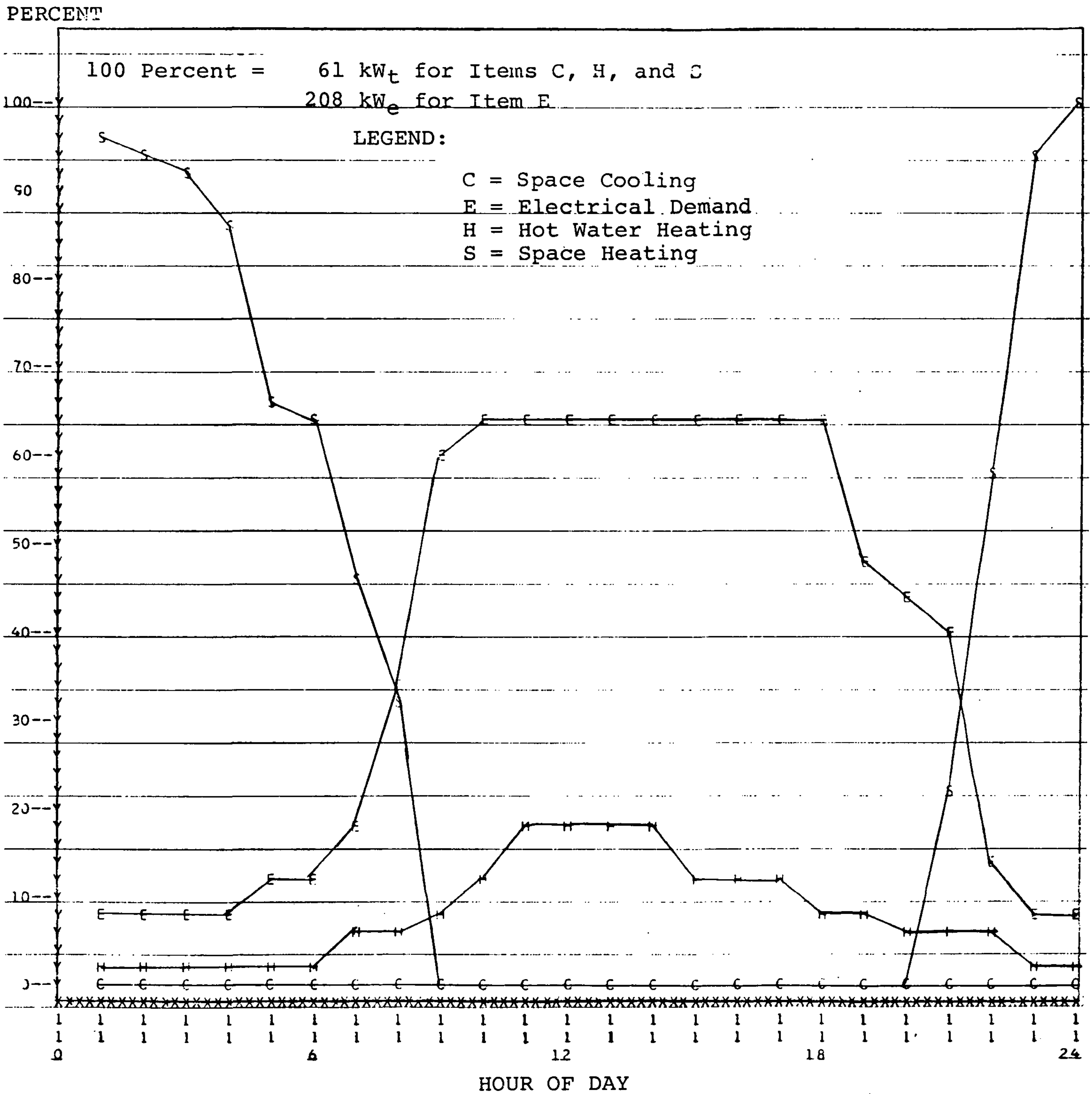


FIGURE D-8

TYPICAL HOURLY LOAD PROFILE

BUILDING: Retail Store
LOCATION: Washington, D.C.
SEASON: Summer

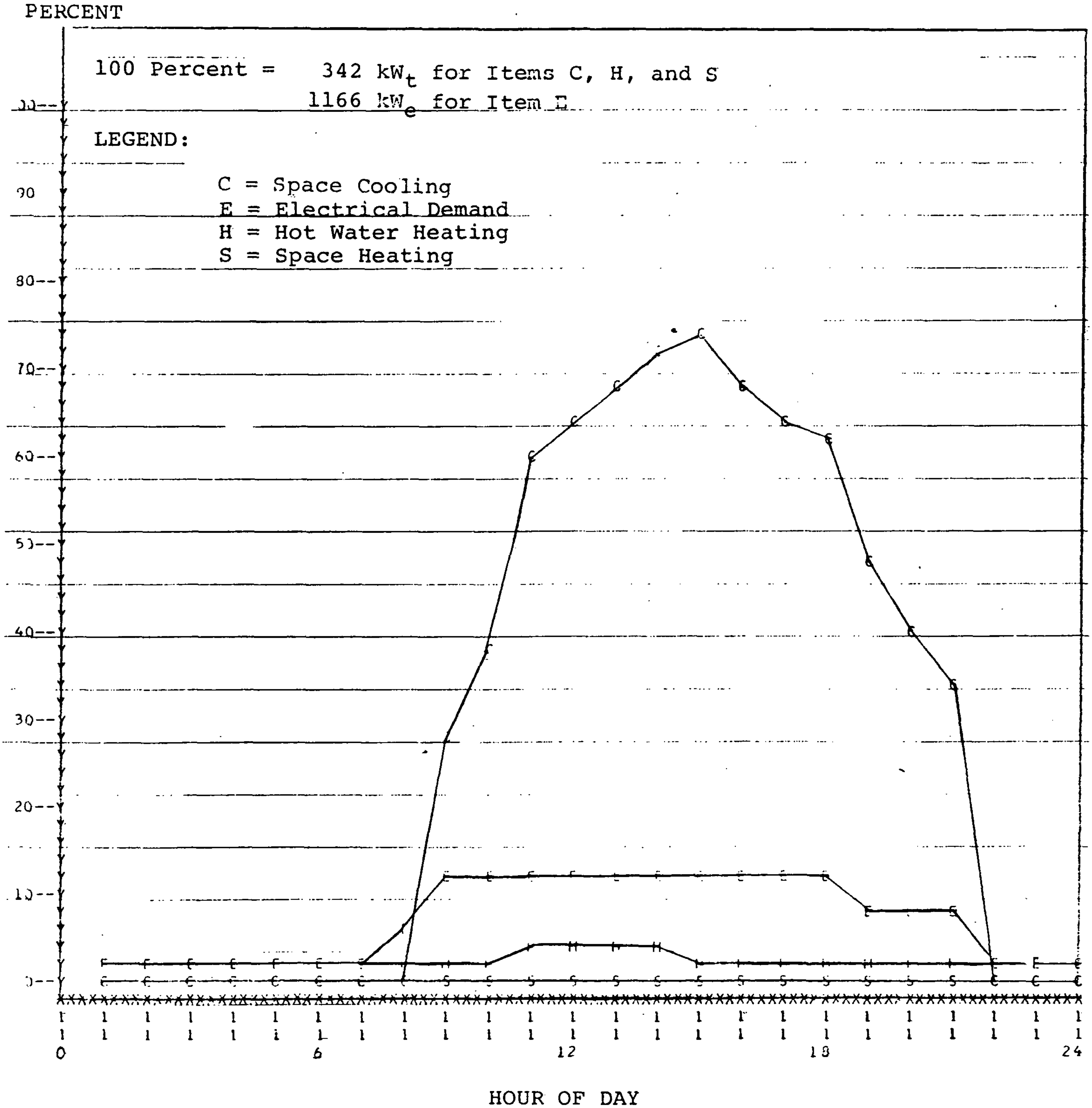


FIGURE D-9

TYPICAL HOURLY LOAD PROFILE

BUILDING: Retail Store
LOCATION: Chicago, Illinois
SEASON: Winter

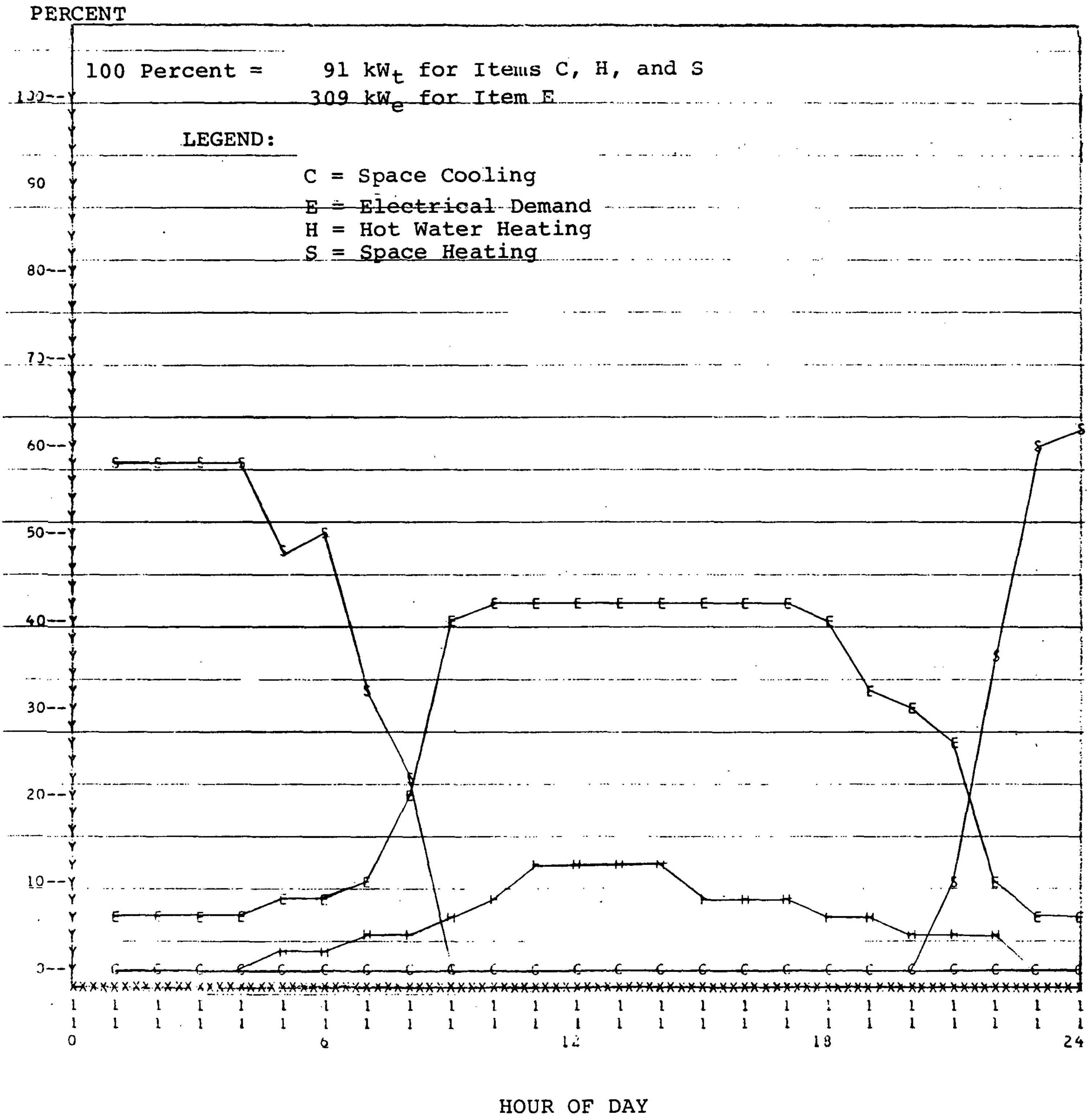


FIGURE D-10

TYPICAL HOURLY LOAD PROFILE

BUILDING: Retail Store
LOCATION: Chicago, Illinois
SEASON: Summer

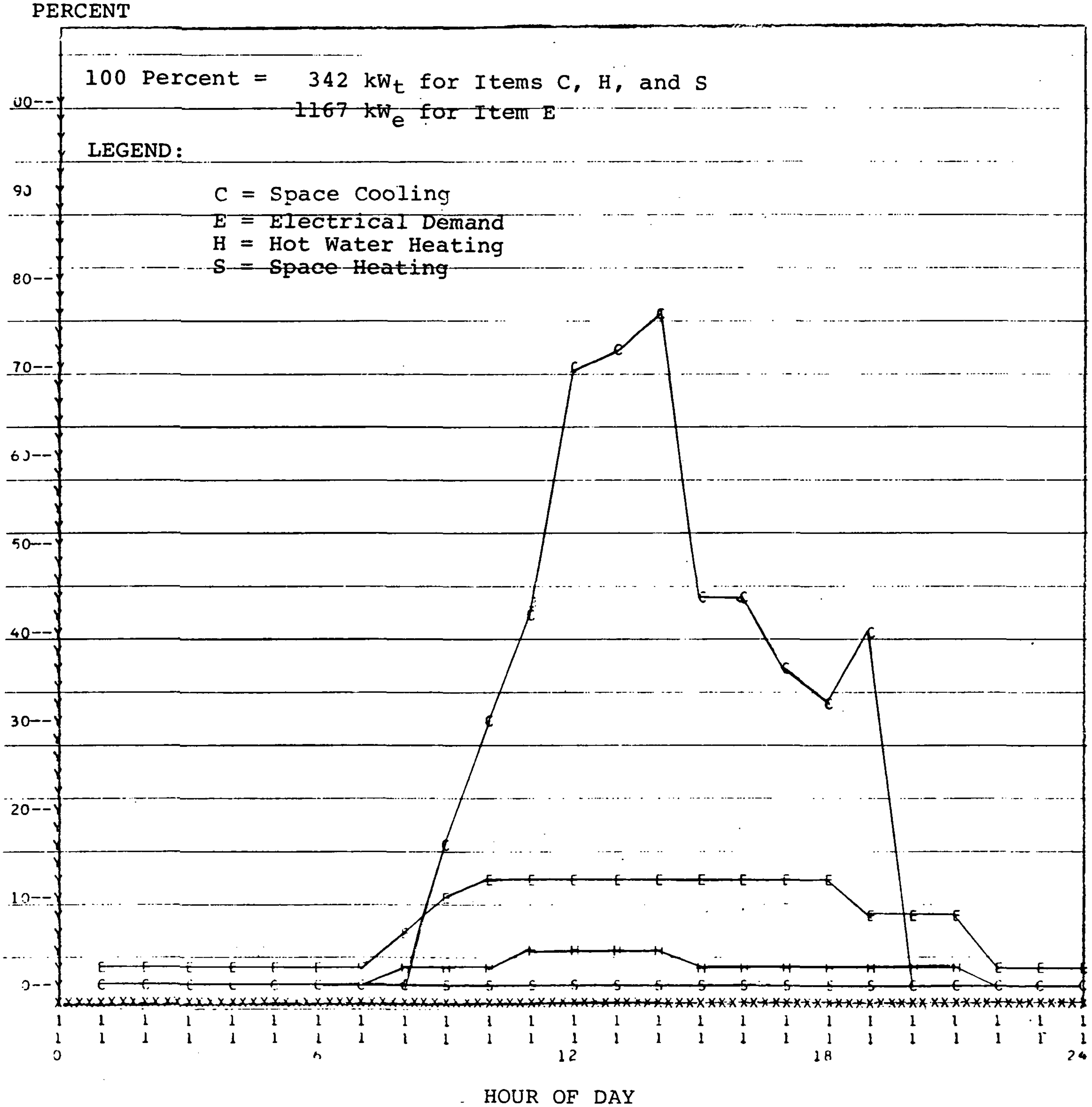


FIGURE D-11

TYPICAL HOURLY LOAD PROFILE

BUILDING: Retail Store
LOCATION: Dallas, Texas
SEASON: Winter

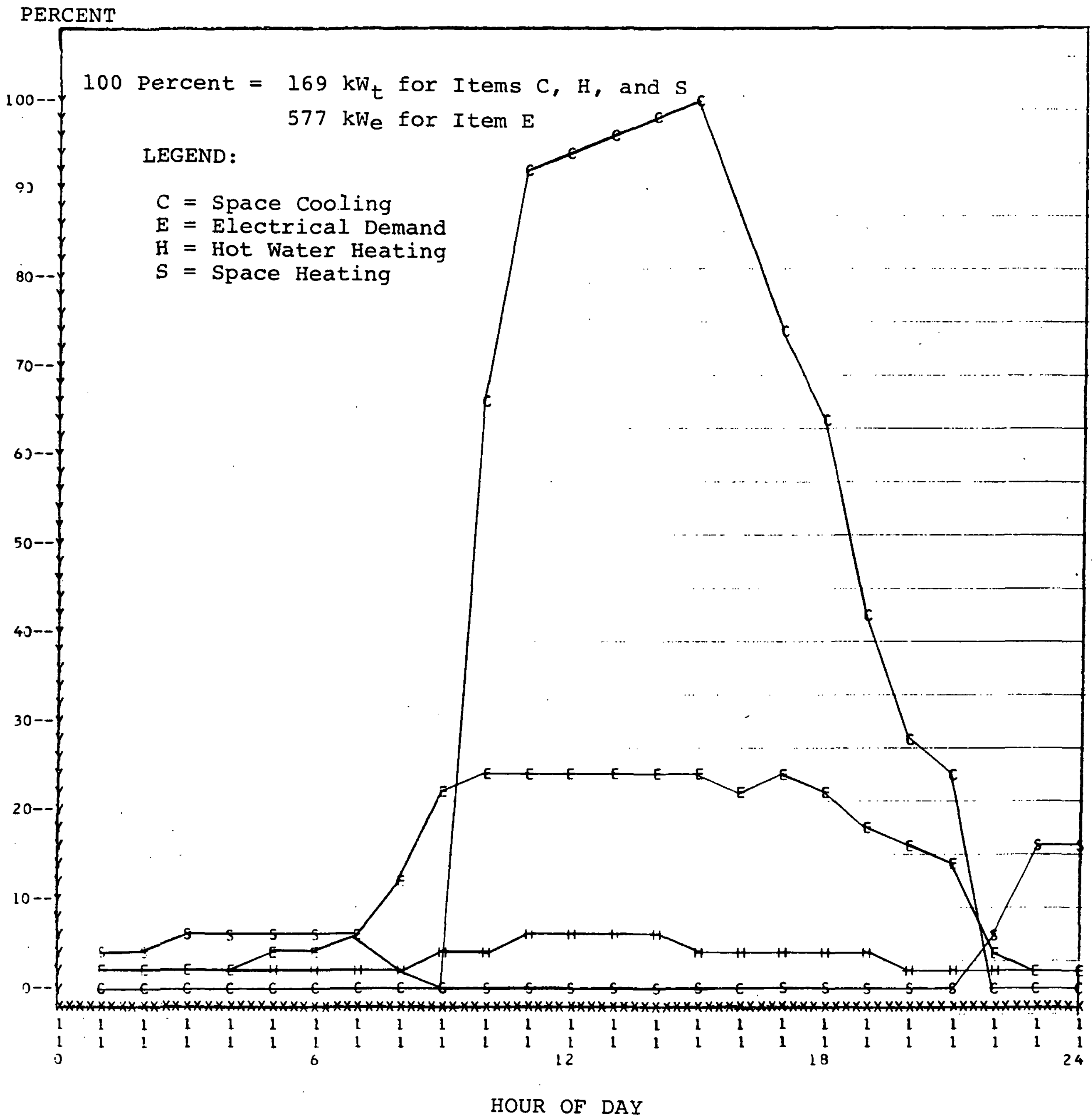


FIGURE D-12

TYPICAL HOURLY LOAD PROFILE

BUILDING: Retail Store
LOCATION: Dallas, Texas
SEASON: Summer

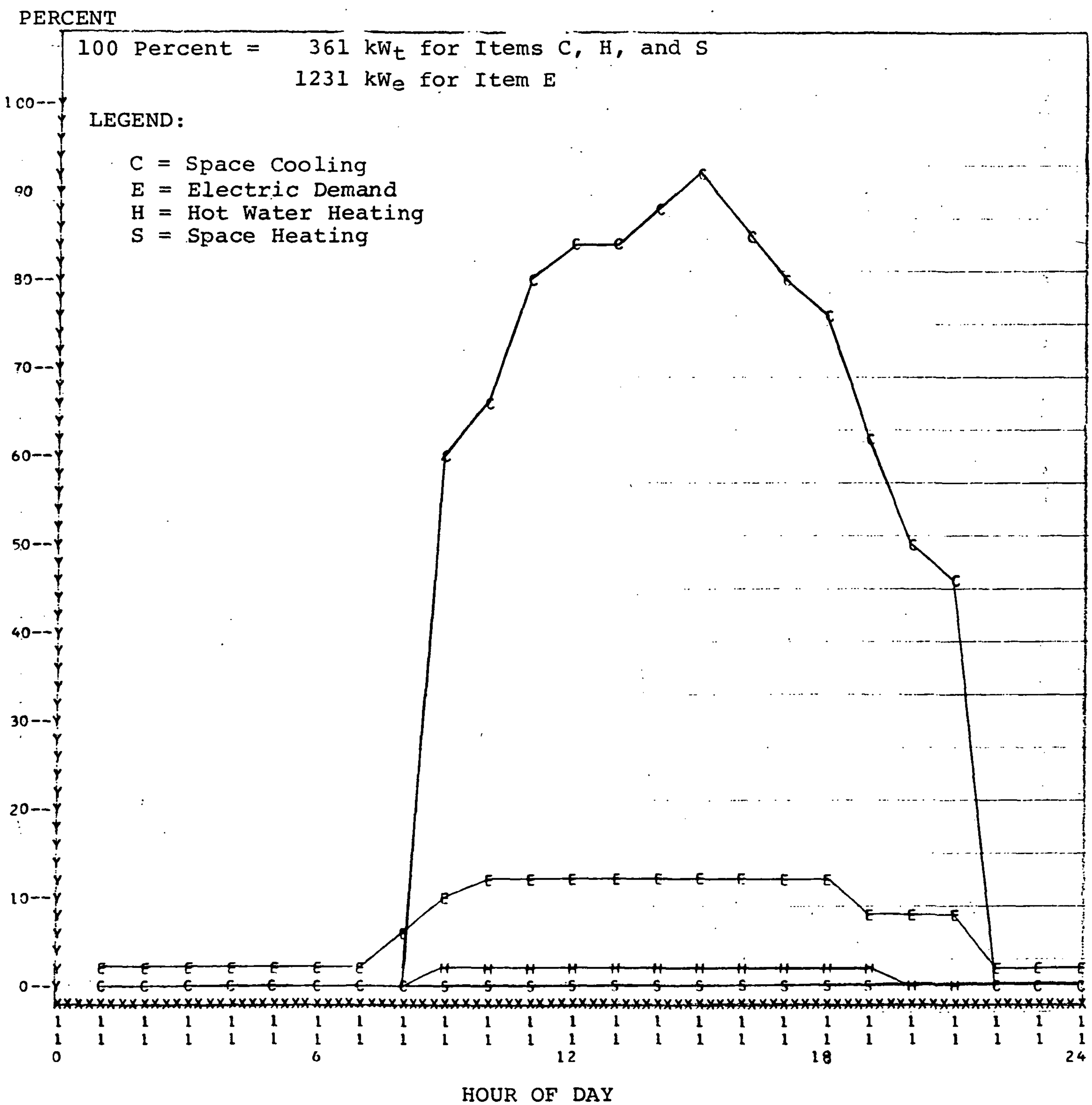


FIGURE D-13

TYPICAL HOURLY LOAD PROFILE

BUILDING: Hospital
LOCATION: Washington, D.C.
SEASON: Winter

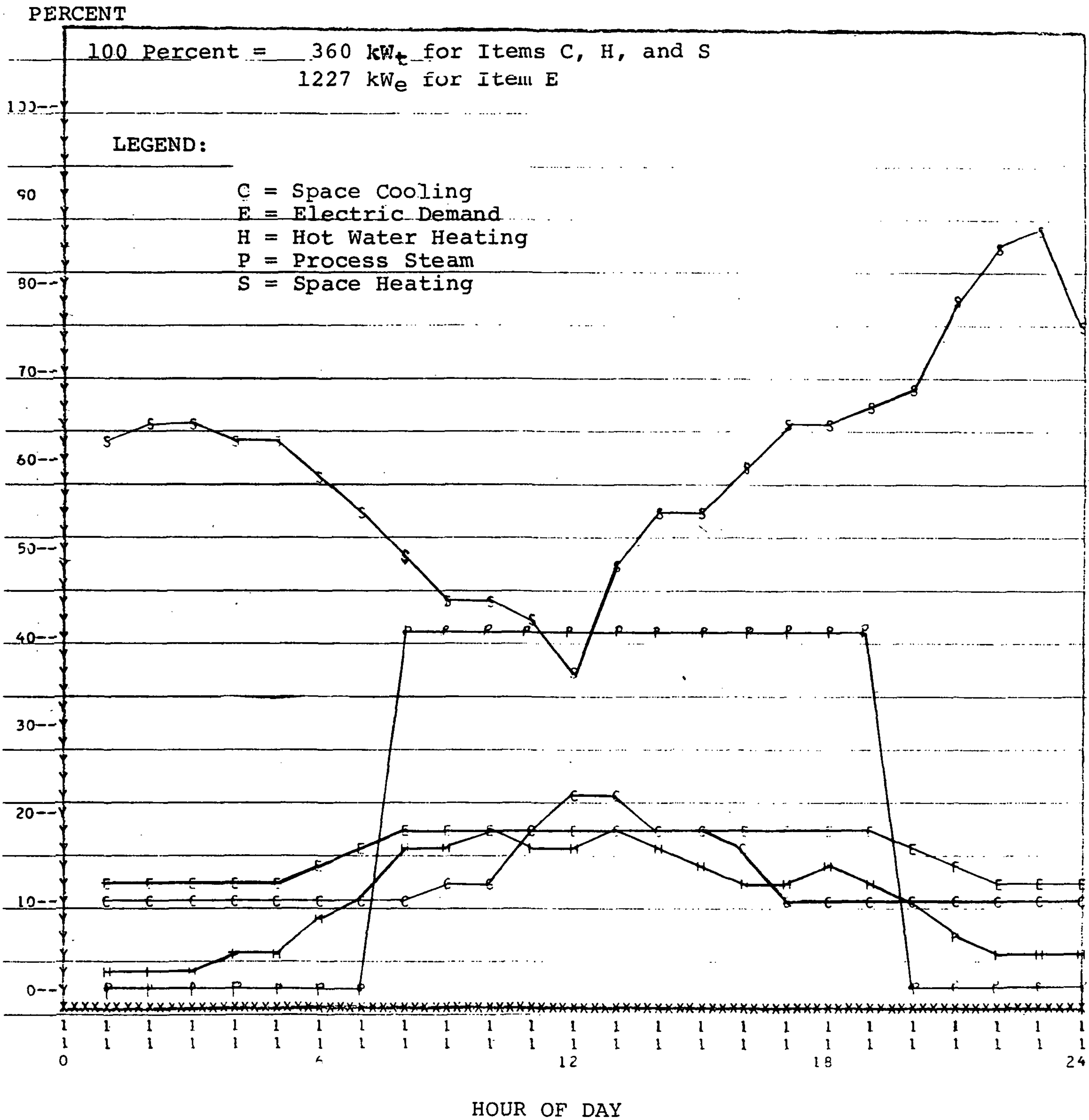


FIGURE D-14

TYPICAL HOURLY LOAD PROFILE

BUILDING: Hospital
LOCATION: Washington, D.C.
SEASON: Summer

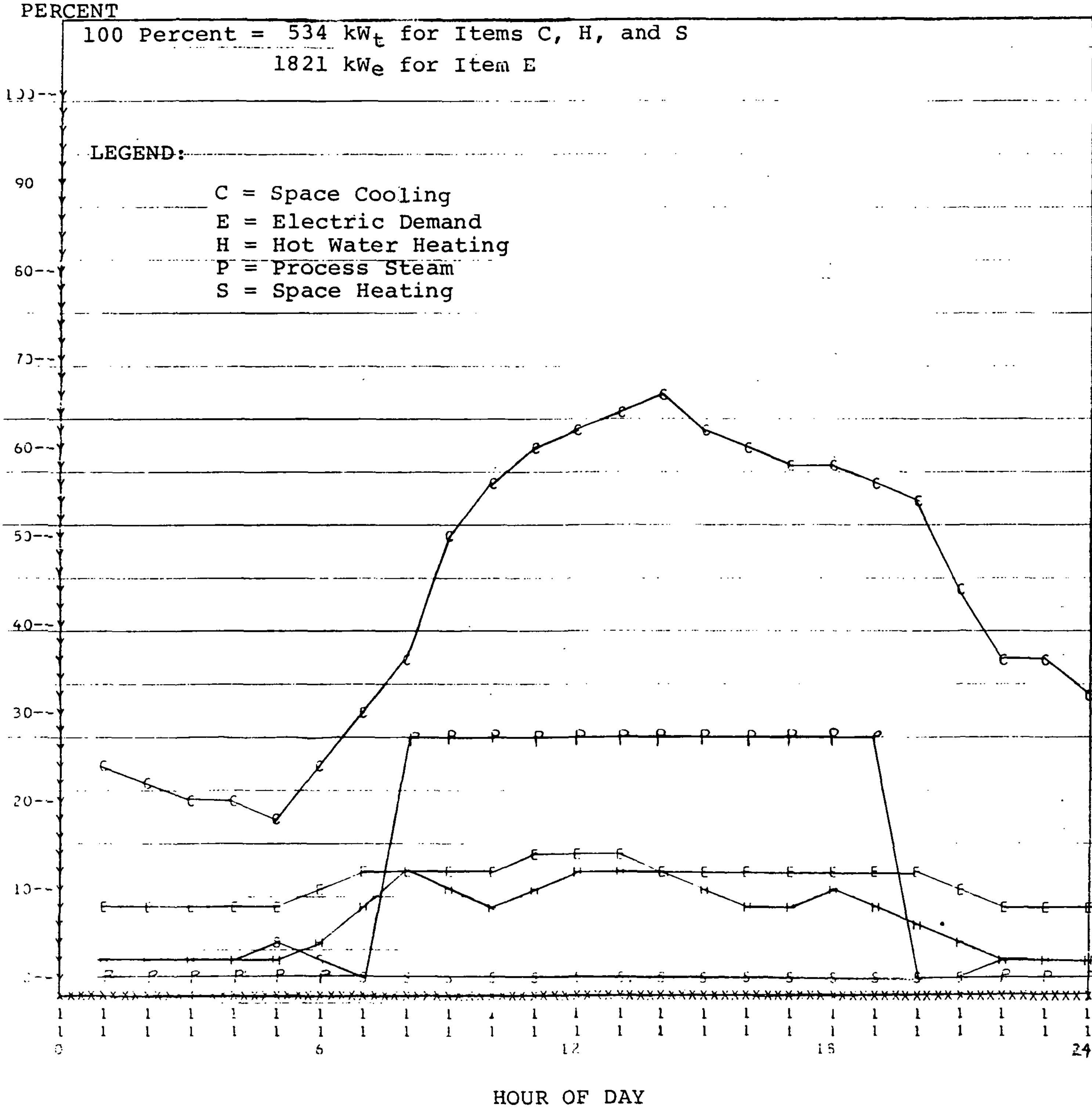


FIGURE D-15

TYPICAL HOURLY LOAD PROFILE

BUILDING: Hospital
LOCATION: Chicago, Illinois
SEASON: Winter

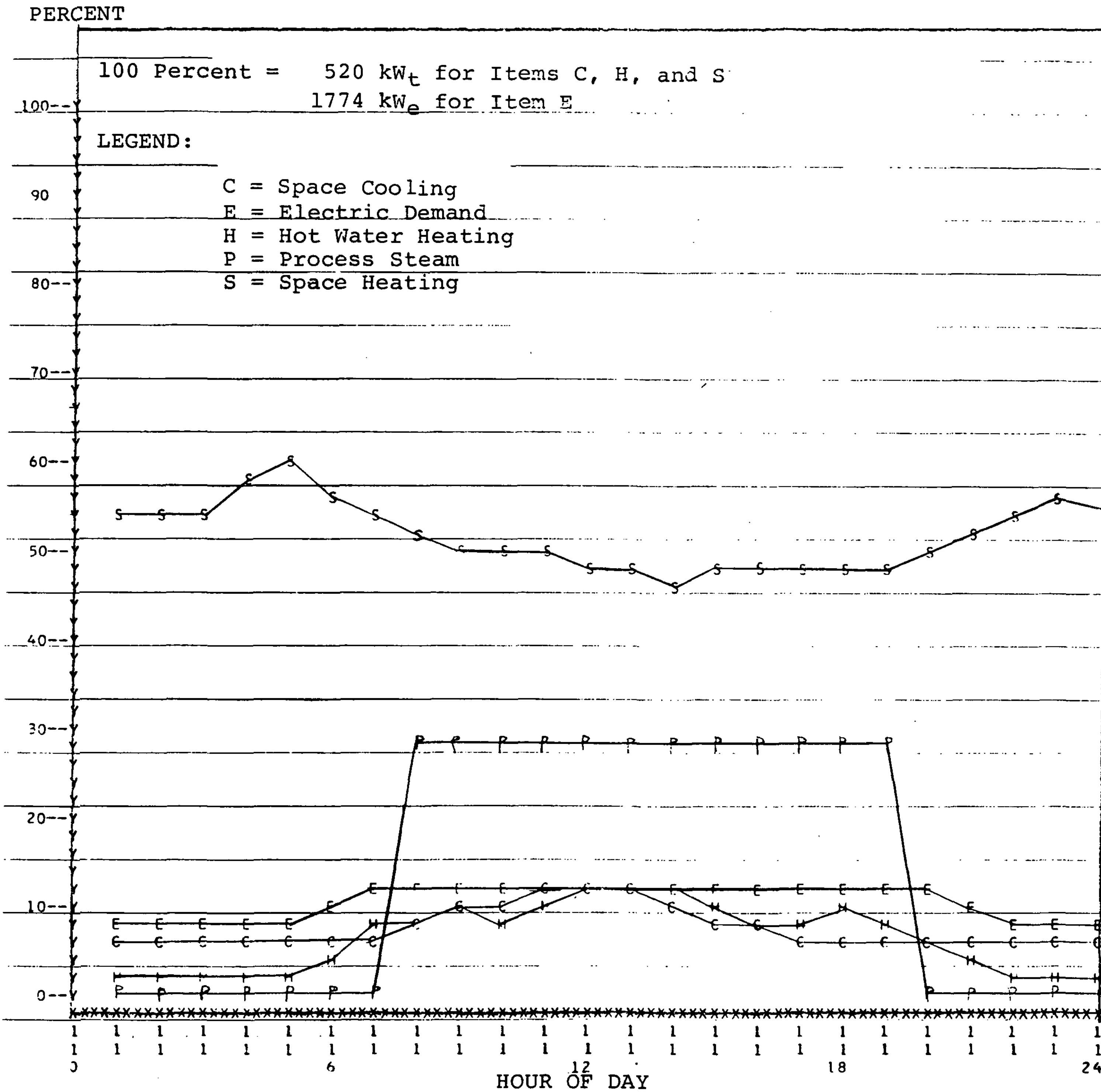


FIGURE D-16

TYPICAL HOURLY LOAD PROFILE

BUILDING: Hospital
LOCATION: Chicago, Illinois
SEASON: Summer

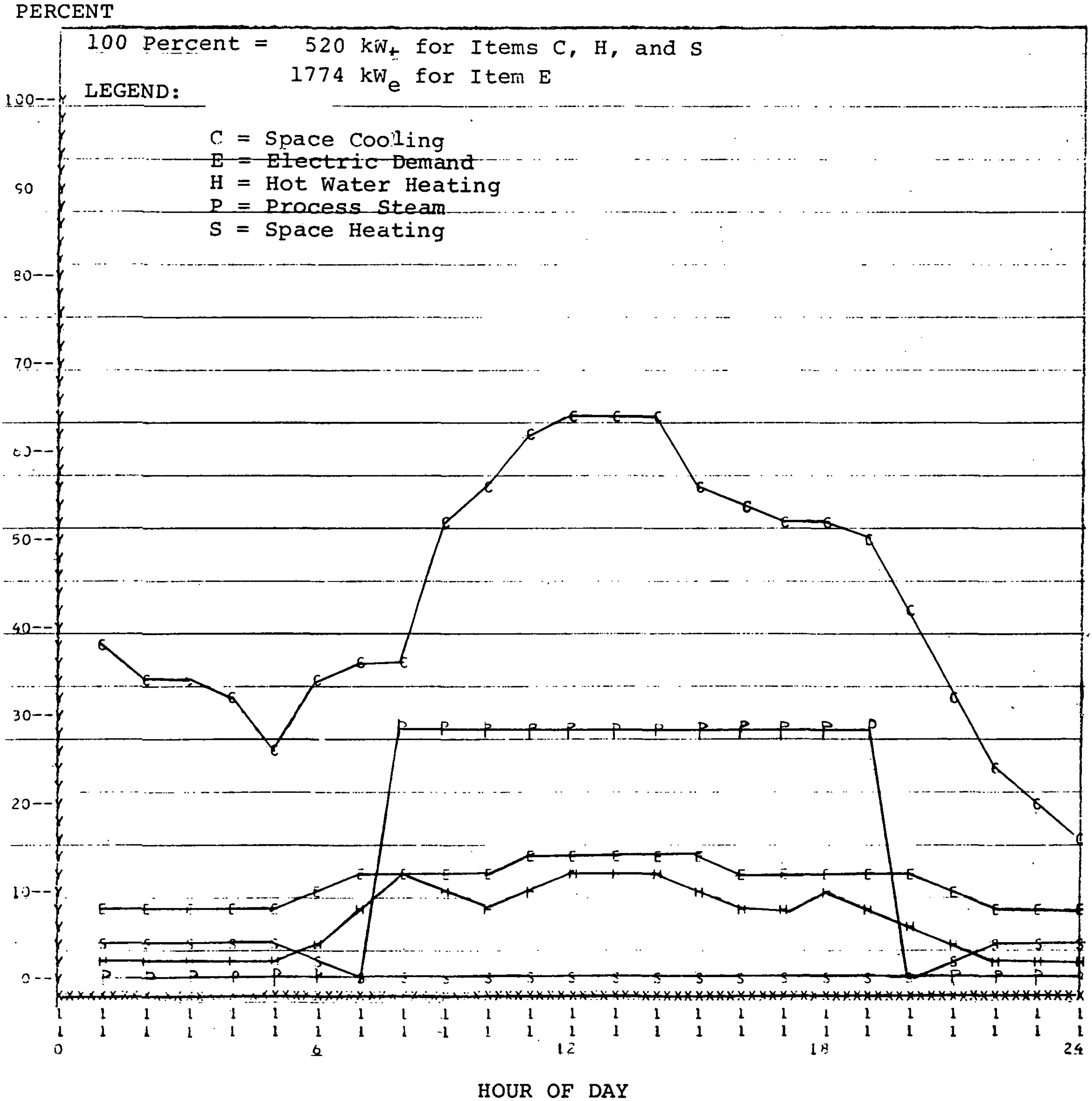


FIGURE D-17

TYPICAL HOURLY LOAD PROFILE

BUILDING: Hospital
LOCATION: Dallas, Texas
SEASON: Winter

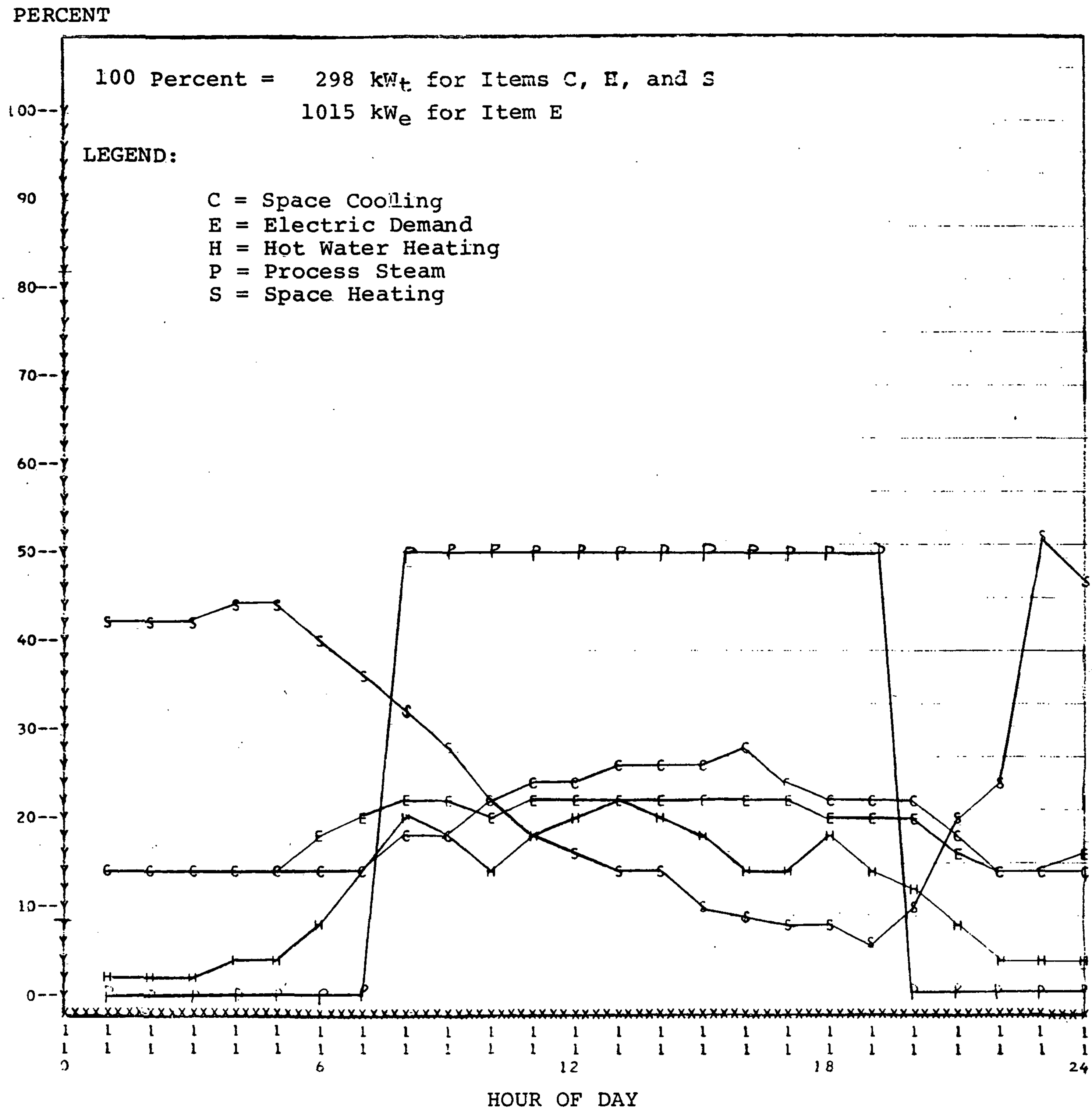
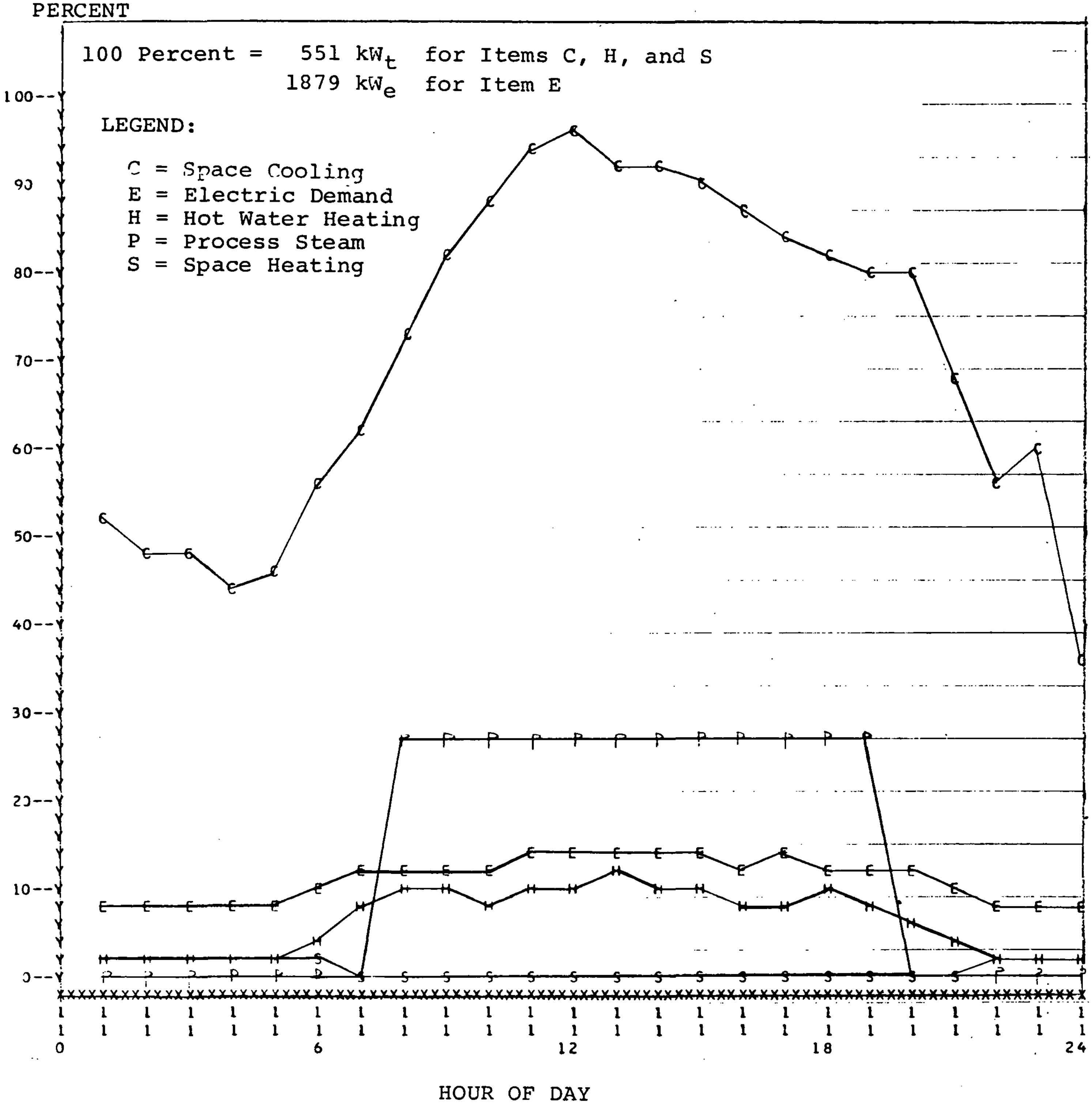


FIGURE D-18

TYPICAL HOURLY LOAD PROFILE

BUILDING: Hospital
LOCATION: Dallas, Texas
SEASON: Summer



APPENDIX E

CONVENTIONAL ENERGY SYSTEM EQUIPMENT LISTS

FIGURE E-1

MAJOR EQUIPMENT - LOW-RISE APARTMENT - WASHINGTON, D. C.

EQUIPMENT	QUANTITY	ELECTRICAL SERVICE
● ALL-ELECTRIC SYSTEM		
- Heat Pump, Air-Air, 2-Ton, Remote Condensor, Supplementary Resistance Heating	24	240V, 1Ø
- Electrical Panelboard 150A	24	240/120V, 1Ø
● GAS-ELECTRIC		
- Gas-Fired Air Furnance with DX Cooling Unit, Remote Condensor 40,000 BTU H Heating, 24,000 BTU H Cooling	24	240/120V, 1Ø + Gas
- Electrical Panelboard 100A	24	240/120, 1Ø

FIGURE E-2

MAJOR EQUIPMENT - RETAIL STORE - WASHINGTON, D.C.

ALL-ELECTRIC

EQUIPMENT	QUANTITY	SERVICE
• REVERSIBLE HEAT PUMP, AIR-AIR, 25-TON INTEGRAL CONDENSOR, SUPPLEMENTARY RESISTANCE HEATING	15	480V, 3Ø
• TRANSFORMER, EXTERIOR, OIL-FILLED, 1,000 KVA, 13.2 KV TO 480/277V	1	13.2 KV
• DISTRIBUTION PANEL FOR HEAT PUMPS	1	480 V
• EMERGENCY GENERATOR, DIESEL, 30 KW 3-PHASE, 4-WIRE	1	DIESEL

FIGURE E-3

MAJOR EQUIPMENT - RETAIL STORE - WASHINGTON, D. C.

GAS-ELECTRIC

EQUIPMENT	QUANTITY	SERVICE
• 360-Ton Electric Centrifugal Chiller	1	480V/3Ø
• 360-Ton Cooling Tower	1	480V/3Ø
4,320 MBH - Cooling	1	480V/3Ø
• Gas-Fired Boiler 1,050 MBH - Heating	1	480V/3Ø
• Roof Top Air Handler, 10,000 cfm, with Chilled Water Cooling Coils and Hot Water Heating Coils and Economizer Cycle, 360 MBH - Cooling, 90 MBH - Heating	12	480V/3Ø
• Supply Fan, 5 HP	12	480V/3Ø
• Transformer, Exterior, Oil-Filled, 1500 KVA, 13.2 KV to 480/277 V	1	13.2 KV
• Emergency Generator, Diesel, 30 KW 3-phase, 4-wire	1	Diesel

FIGURE E-4

MAJOR EQUIPMENT - HOSPITAL - WASHINGTON, D. C.

ALL ELECTRIC

EQUIPMENT	QUANTITY	SERVICE
• Heat Pump, Water-Air, 40-Ton Roof-Mounted, 491 MBH Cooling, 464 MBH Heating	13	480V/3Ø
• Supply Fan	13	480V/3Ø
• Return Fan	13	480V/3Ø
• Compressor	13	54 KW
• Heat Pump, Water-Air, 4-Ton, Horizontal Cooling, 48 MBH Cooling, 58 MBH Heating	15	480V/3Ø
• Closed Circuit Evaporative Cooler with Fan Motor and Spray Pump	1	480V/3Ø
• Auxiliary Water Heater, 4000 MBH	1	480V/3Ø
• Closed Loop Circulating Pump	1	480V/3Ø
• Unit Heaters, Electric	5	480V/3Ø
• Transformer, 2000 KVA, 13.2 KV to 480/277 V	1	13.2 KV
• Switchboard, 3000 Amp	1	480/277V/3Ø
• Emergency Generator Set, 208/120V/3Ø 140 KW	1	Diesel
• Emergency Generator Set, 480V/3Ø 250KW	1	Diesel

FIGURE E-5

MAJOR EQUIPMENT - HOSPITAL - WASHINGTON, D. C.

GAS-ELECTRIC SYSTEM

EQUIPMENT	QUANTITY	SERVICE
• Hermetic Absorption Chiller with Solution Pump, Refrigerant Pump and Chilled Water Pump 6940 MBH - Cooling	1	480V/3Ø
• Cooling Tower (Forced Draft) with Fans and Pumps 6940 MBH - Cooling	1	480V/3Ø
• Gas-Fired Steam Boiler 6900 lb/hr with Boiler Feed Pumps, Hot Water Circ. Pumps and Hot Water Booster Pump	3	480V/3Ø
• Transformer, 750 KVA, 13.2 KV to 480/277V	1	13.2 KV
• Switchboard, 1200 Amp	1	480/277V/3Ø
• Air Handling Units:		
5,500 cfm	1	480V/3Ø
27,300 cfm	1	480V/3Ø
12,700 cfm	1	480V/3Ø
9,500 cfm	1	480V/3Ø
5,500 cfm	1	480V/3Ø
3,400 cfm	1	480V/3Ø
• Unit Heaters, 40 MBH	5	160V/1Ø
• Emergency Generator, 208/120V/3Ø	1	Diesel
• Emergency Generator, 480V/3Ø	1	Diesel

APPENDIX F

HVAC EQUIPMENT PERFORMANCE CHARACTERISTICS

APPENDIX F

HVAC EQUIPMENT PERFORMANCE CHARACTERISTICS

The performance characteristics of certain HVAC equipment were assumed to vary either as a function of operating level or ambient temperature. Specifically, chiller performance was assumed to vary with operating level, and heat pump heating performance was assumed to vary with ambient temperature. Vapor compression and absorption chiller performance assumptions are described in Sections F.1 and F.2, respectively. Heat pump performance assumptions are described in Section F.3.

F.1 Vapor Compression Chiller Performance

Vapor compression chiller performance was assumed to vary with chiller loading as shown below. It was assumed the chiller's coefficient of performance, COP, could be expressed as:

$$COP = \left[(0.9685)x^3 - (0.2351)x^2 + (2.237)x + 1.892\right] \cdot x \qquad (F\text{-}3)$$

where x = equipment operating level, as a fraction of rated load. This performance relation is plotted in Figure F-1.

F.2 Absorption Chiller Performance

The part-load performance characteristics of absorption chillers were approximated using a piecewise linear function of chiller operating level x, as plotted in Figure F-2.

F.3 Heat Pump Heating Performance

Heat pump heating performance was assumed to be relatively constant versus operating level. However, the effect of the ambient

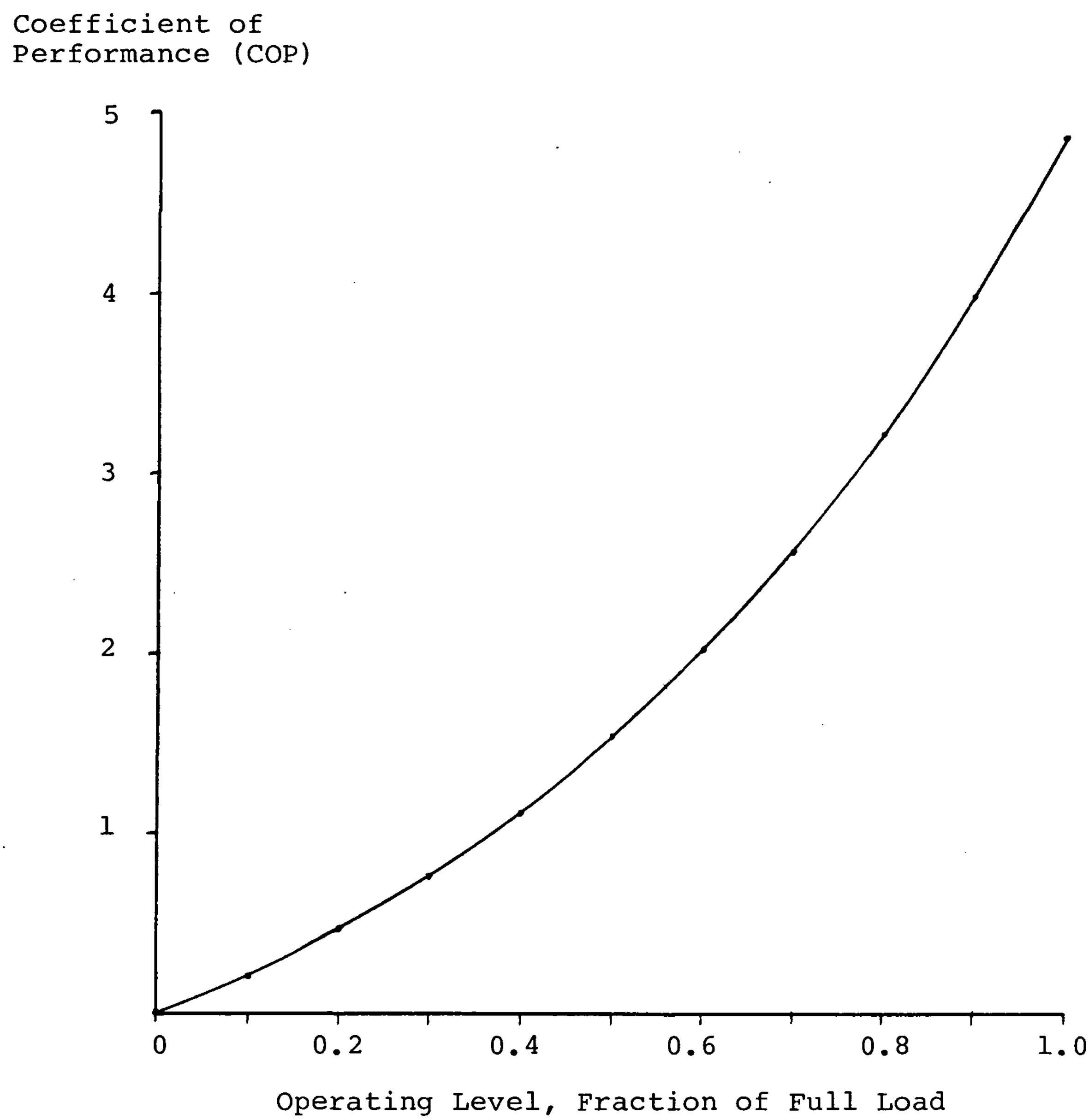


Figure F-1. Vapor Compression Chiller COP versus Operating Level

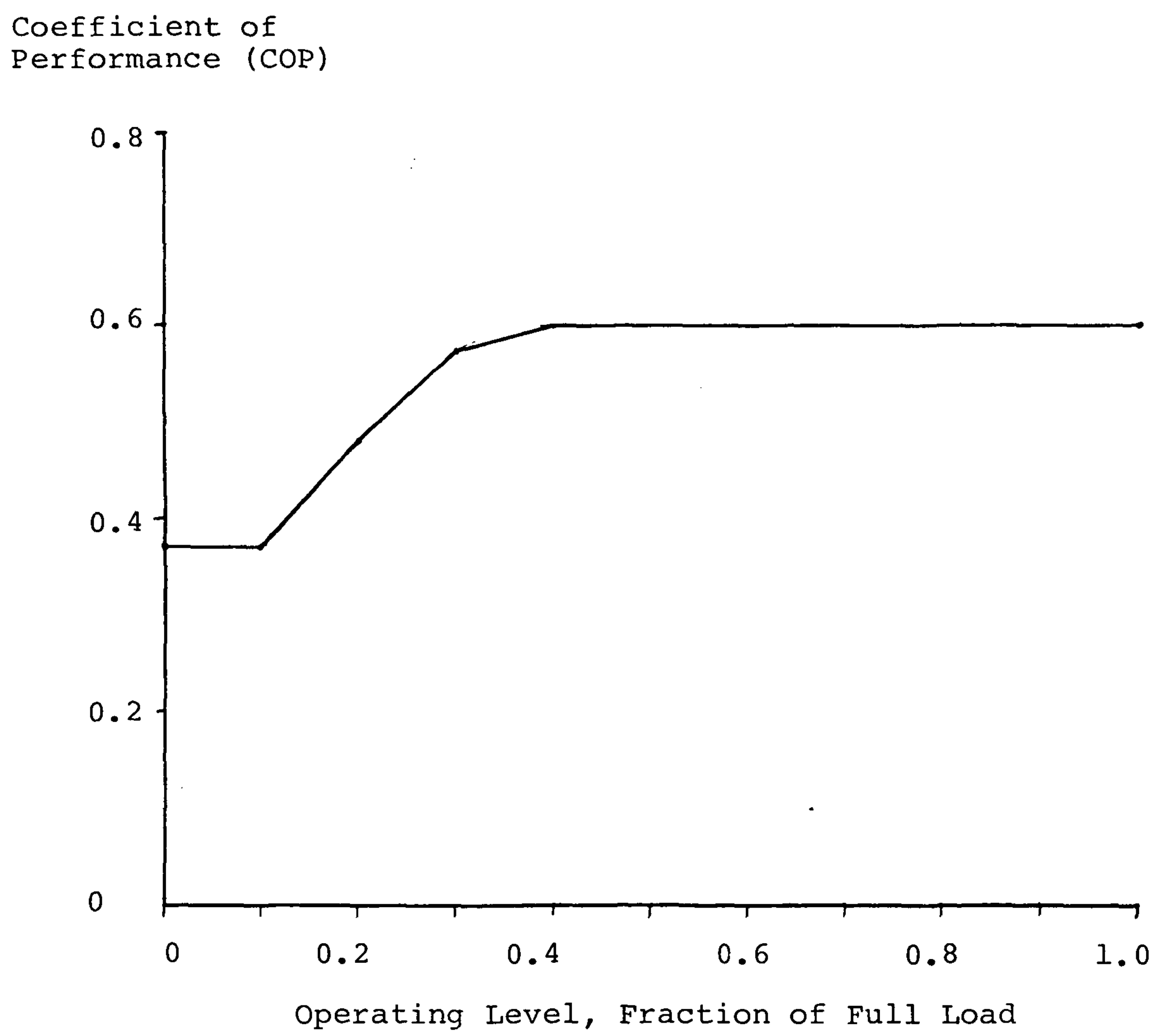


Figure F-2. Absorption Chiller COP versus Operating Level (outside) temperature T_A on heat pump performance was modeled. The assumed functional relationship is plotted in Figure F-3.

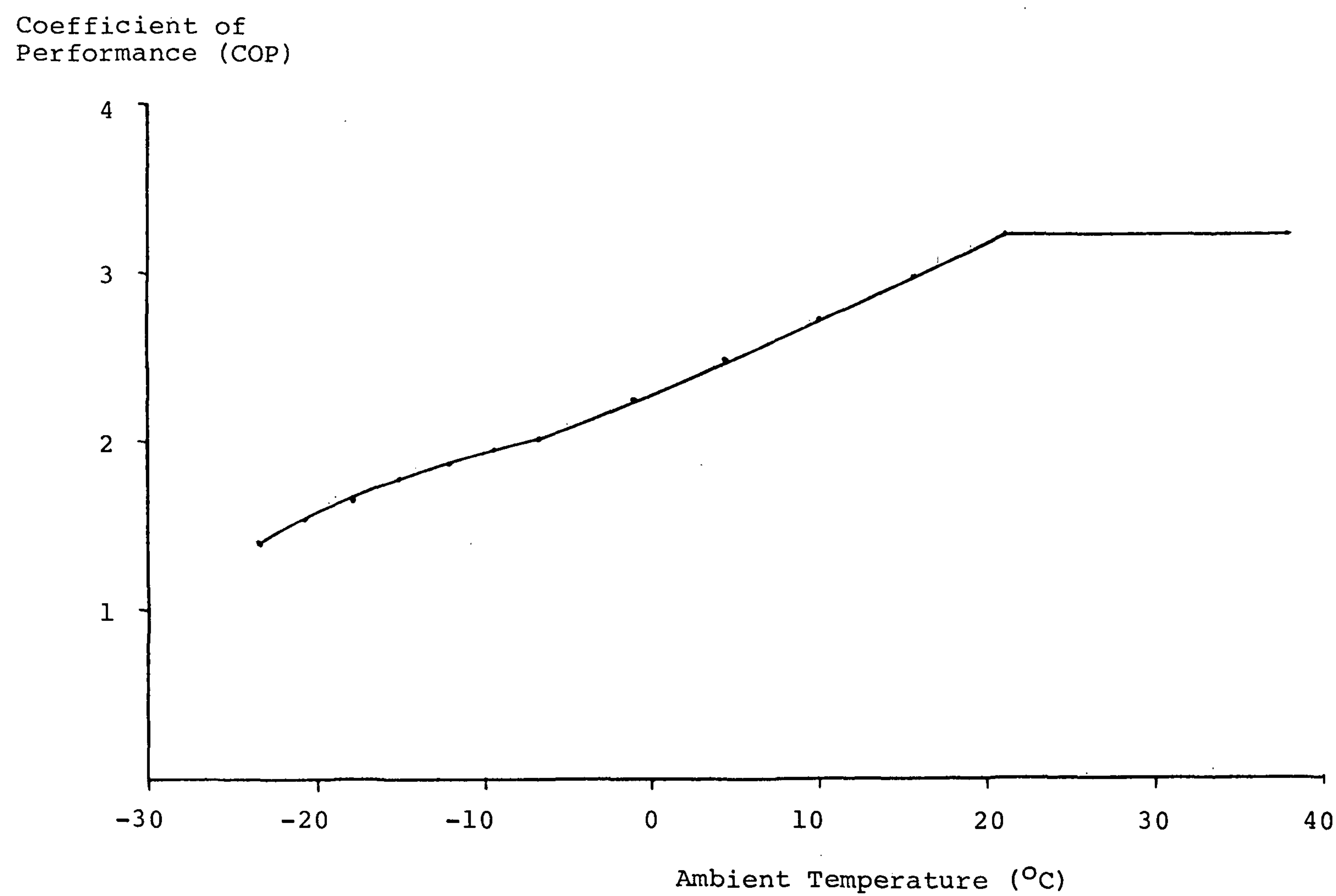
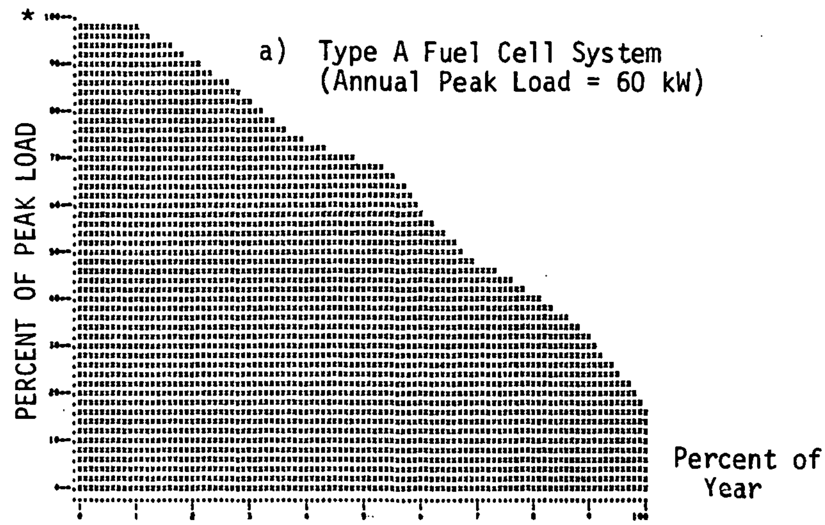
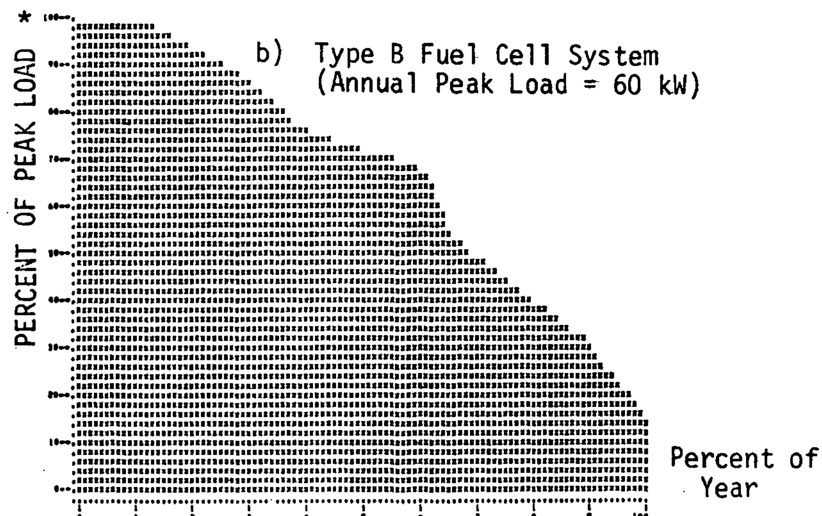


Figure F-3. Heat Pump COP versus Ambient Temperature

APPENDIX G

FUEL CELL LOAD DURATION CURVES





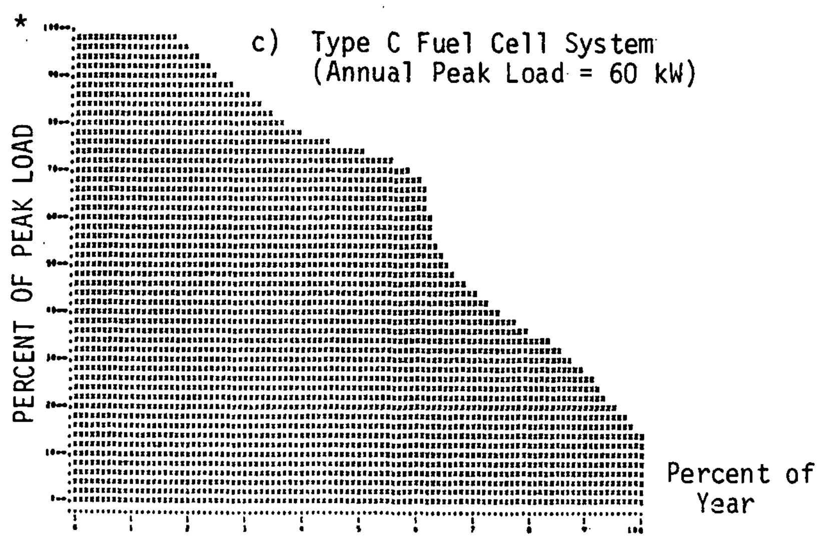


Figure G-1 Annual Load Duration Curve for Low-Rise Apartment Building, Washington, D.C.

* 100% = 60 kW

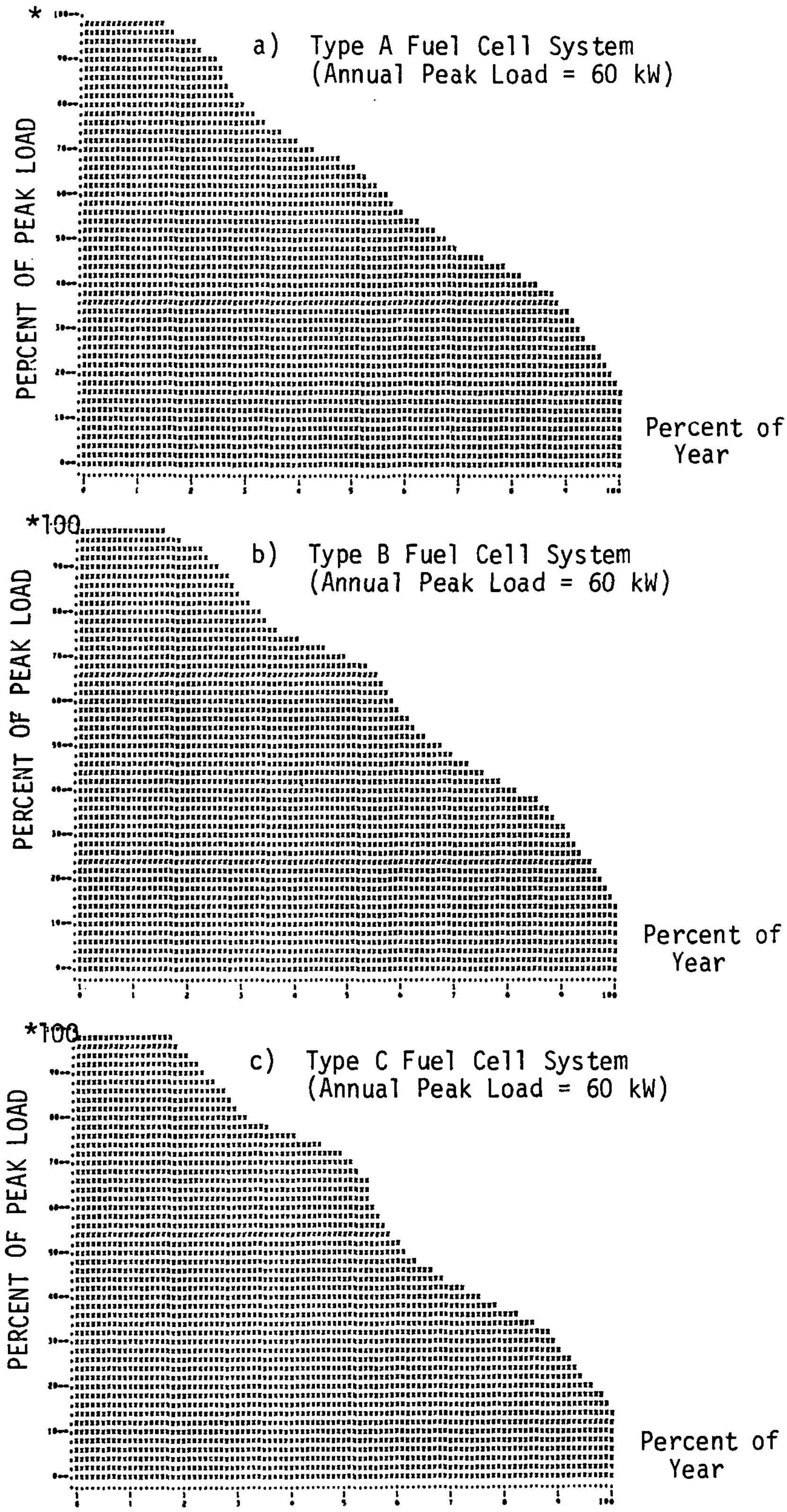
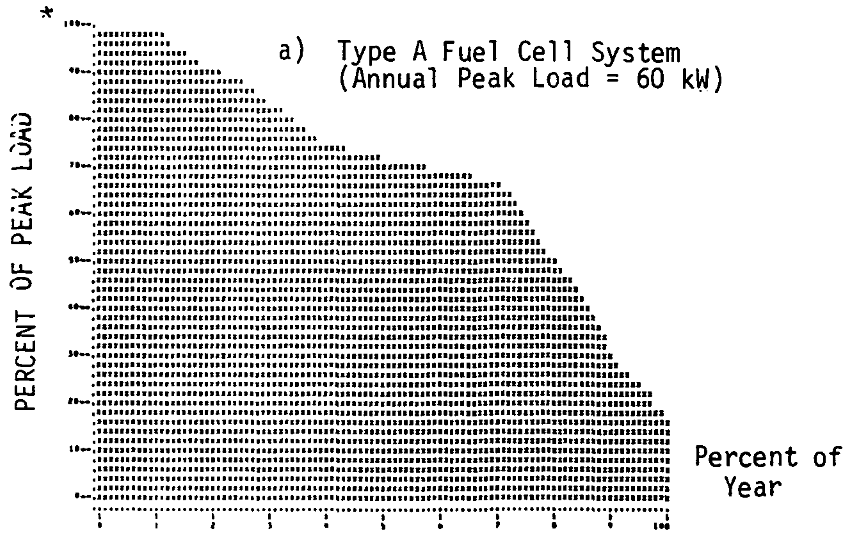
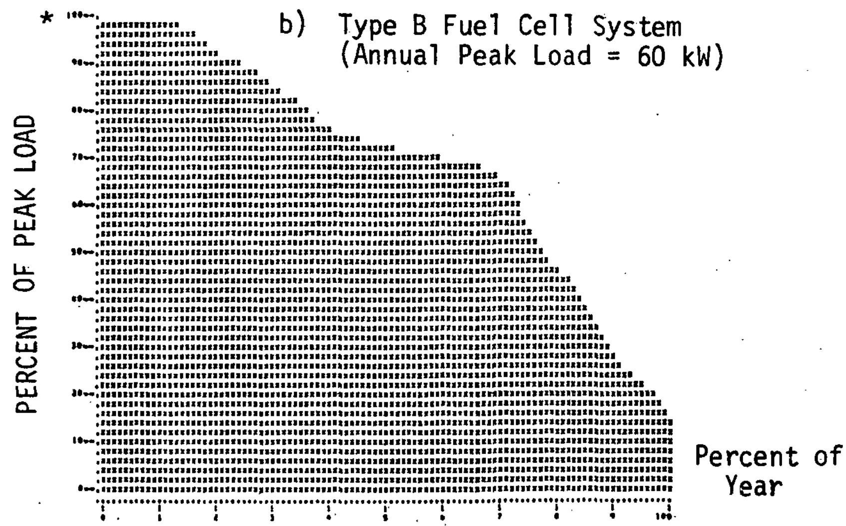


Figure G- 2 Annual Load Duration Curve for Low-Rise Apartment Building, Chicago

* 100% = 60 kW





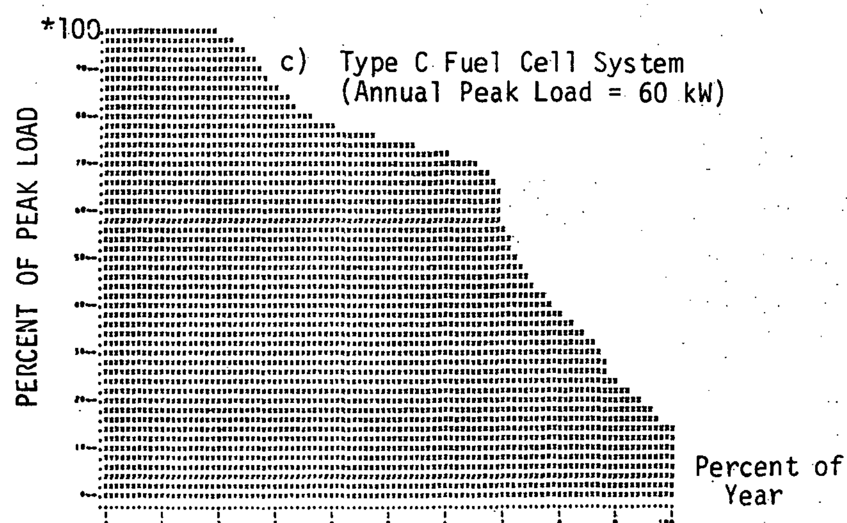


Figure G-3 Annual Load Duration Curve for Low-Rise Apartment Building, Dallas

* 100% = 60 kW

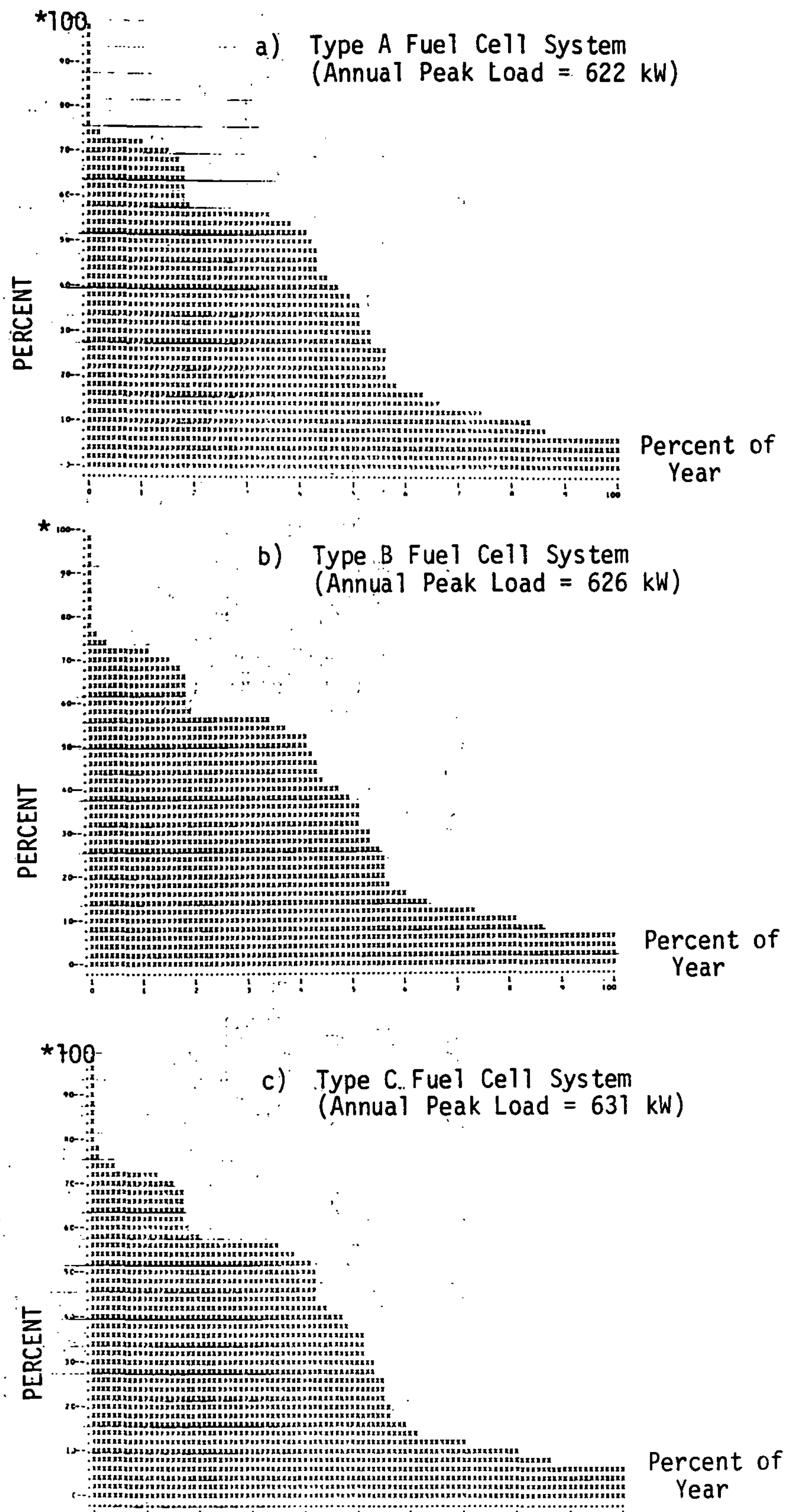


Figure G-4 Annual Load Duration Curve for Retail Store, Washington, D.C.

* 100% = 800 kW

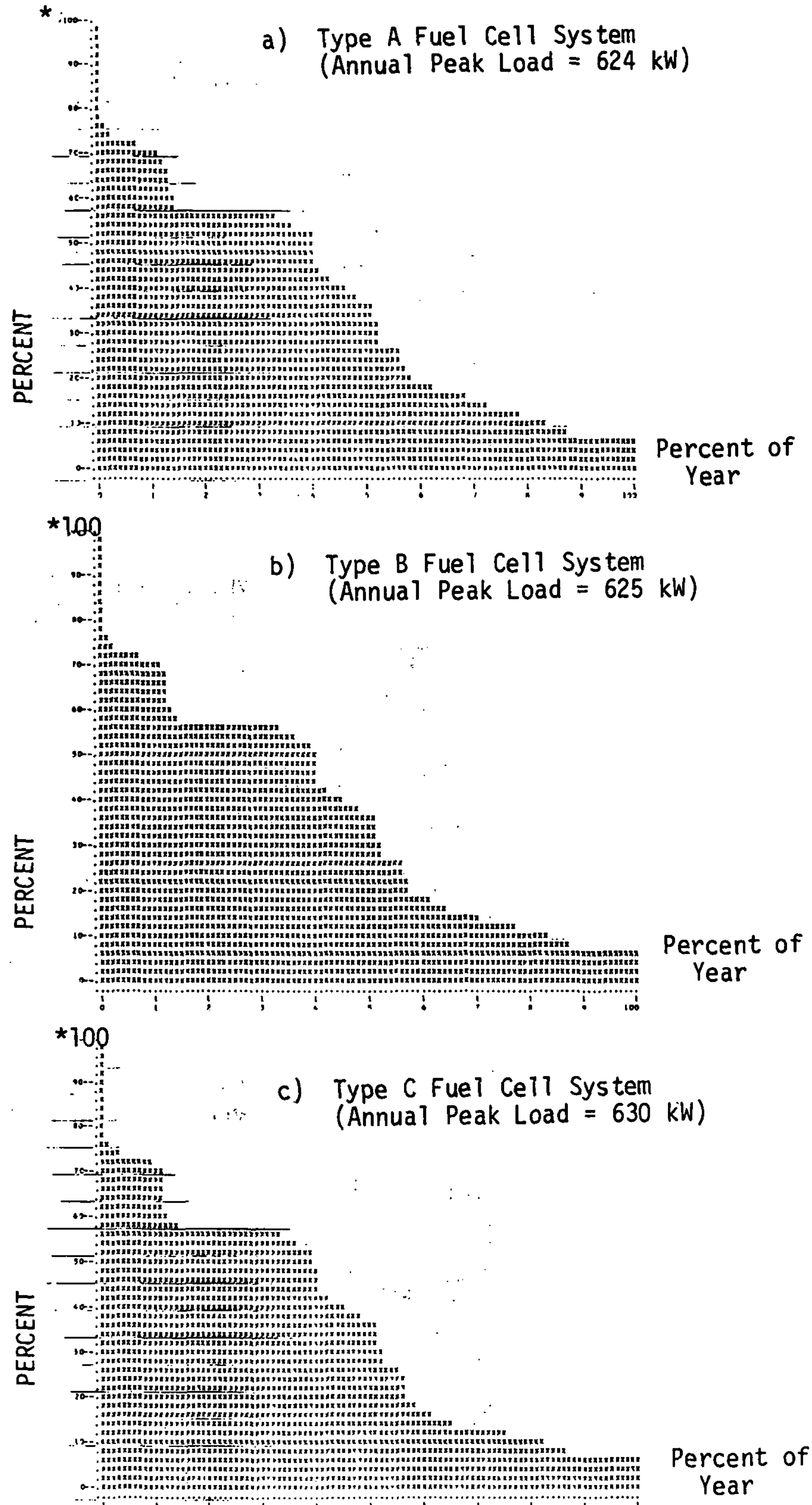


Figure G-5 Annual Load Duration Curve for Retail Store Chicago

* 100% = 800 kW

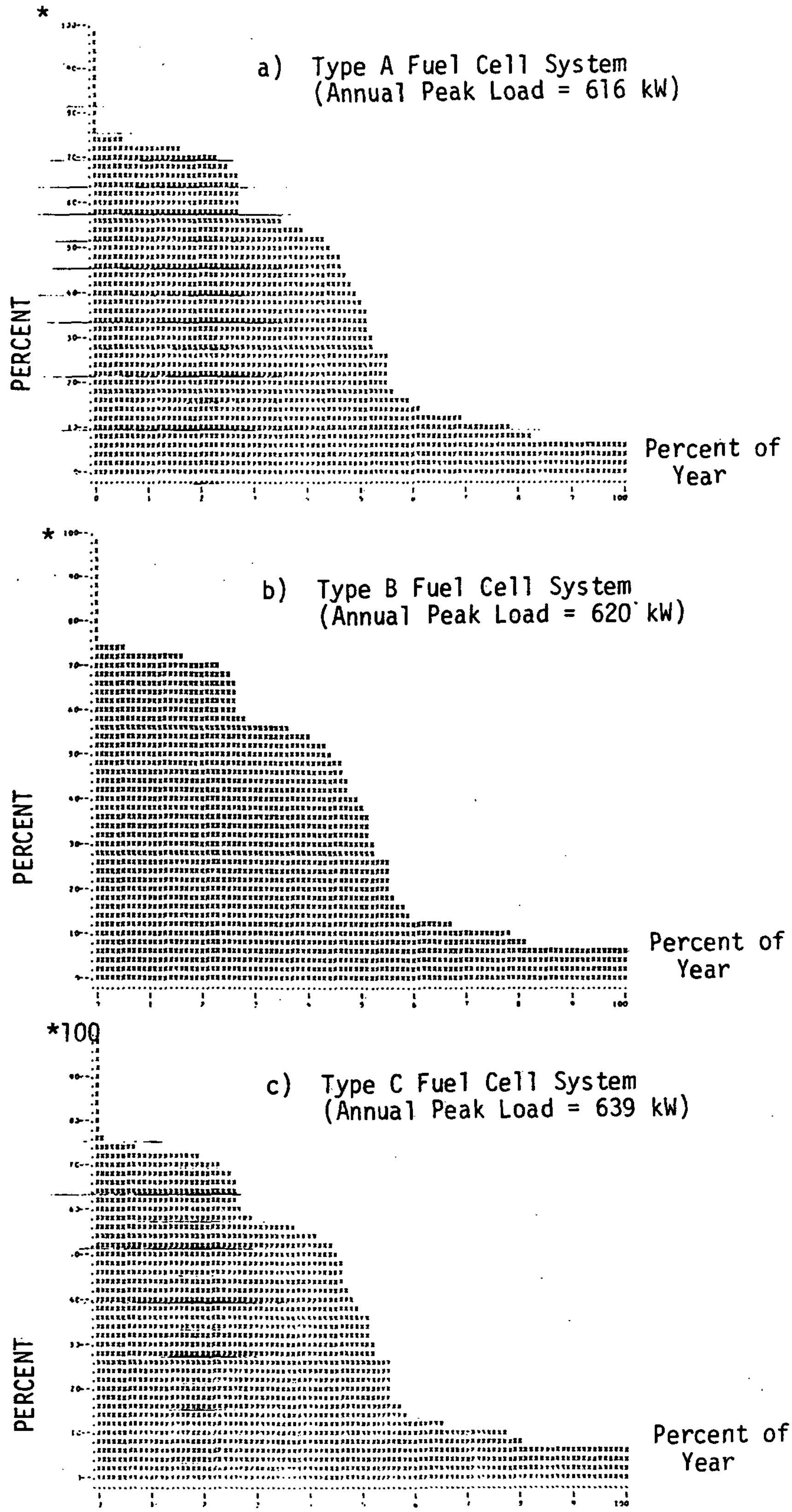


Figure G-6 Annual Load Duration Curve for Retail Store
Dallas

* 100% = 800 kW

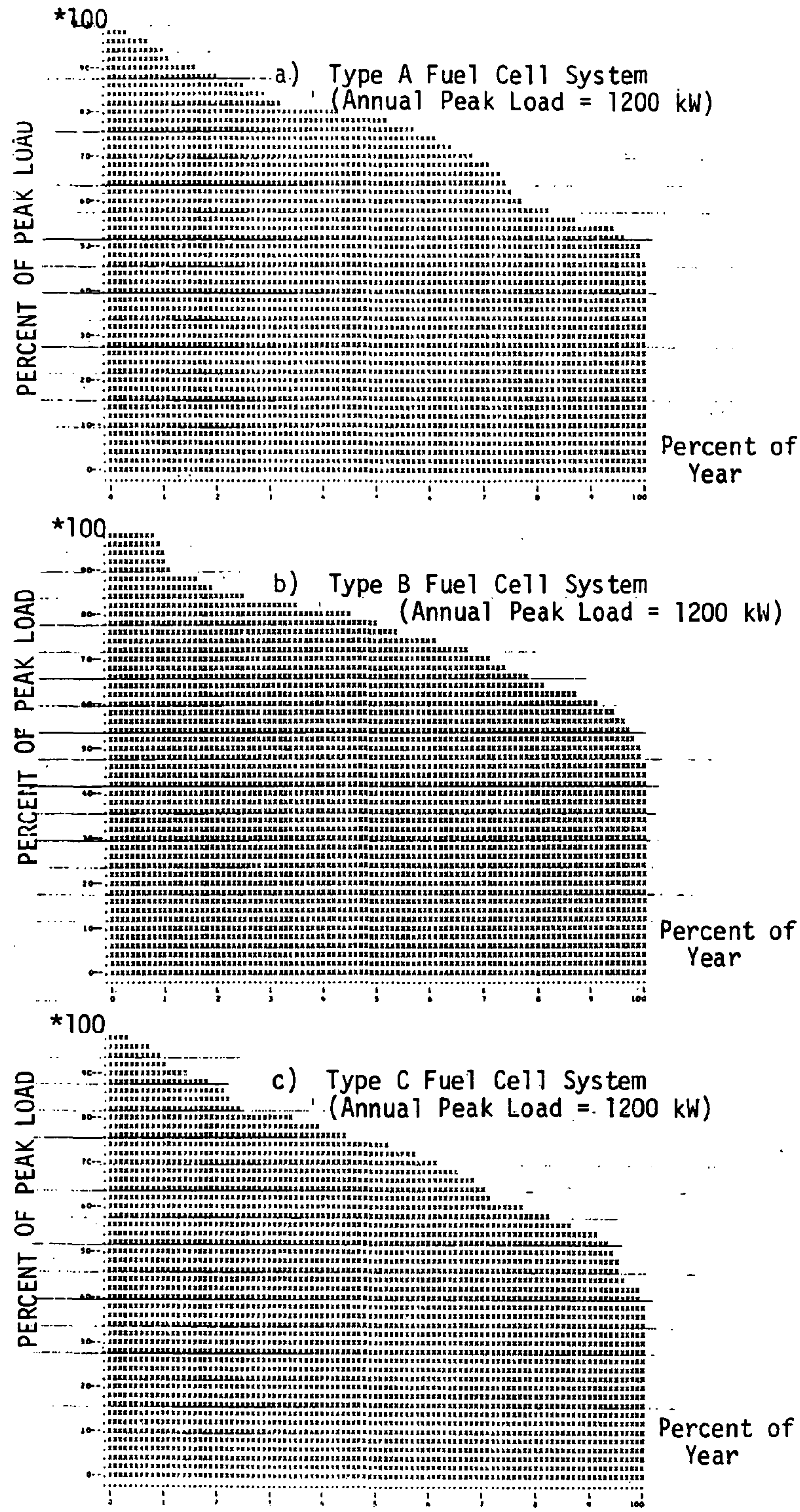


Figure G-7 Annual Load Duration Curve for Hospital, Washington, D.C.

* 100% = 1200 kW

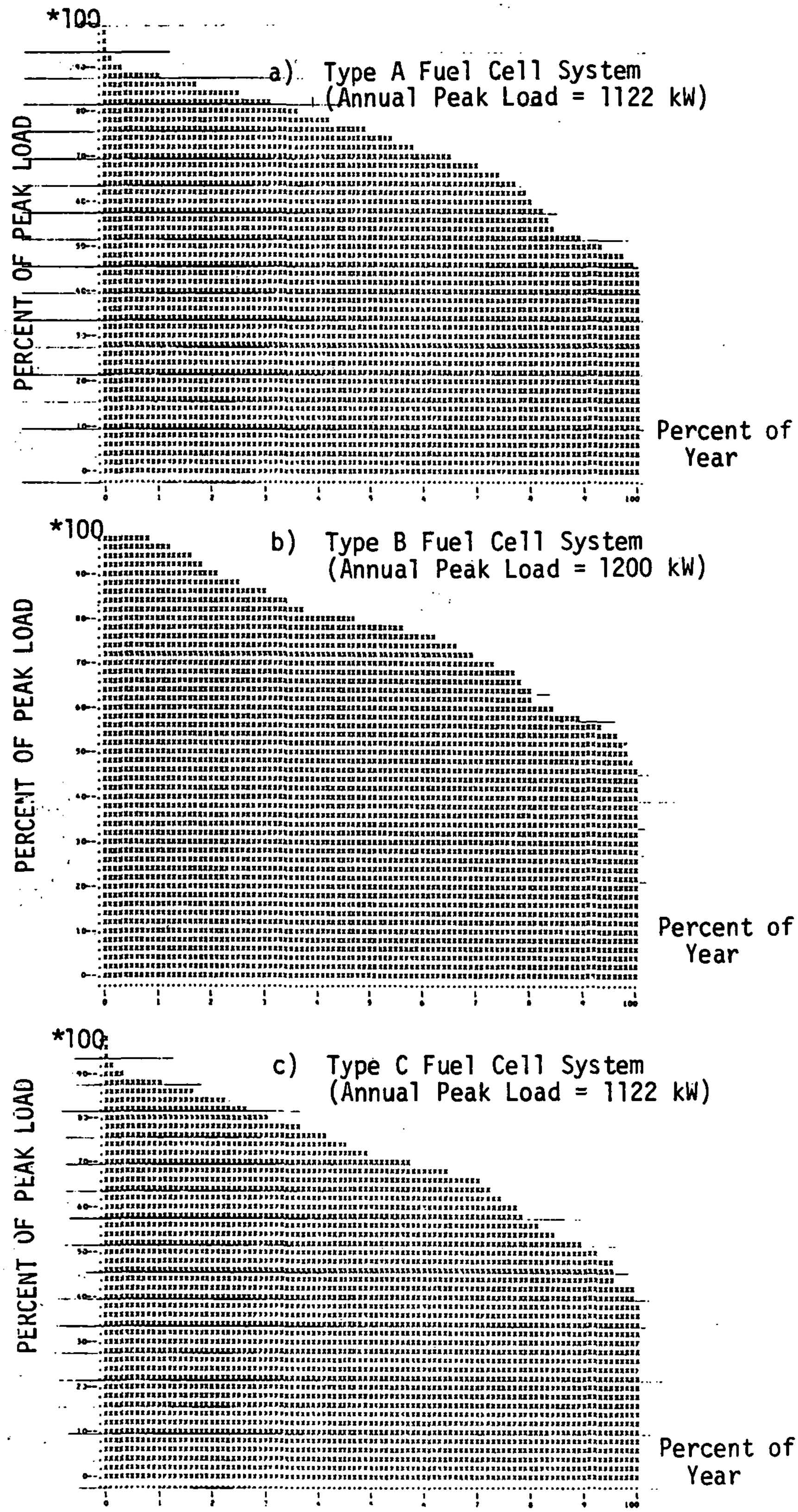
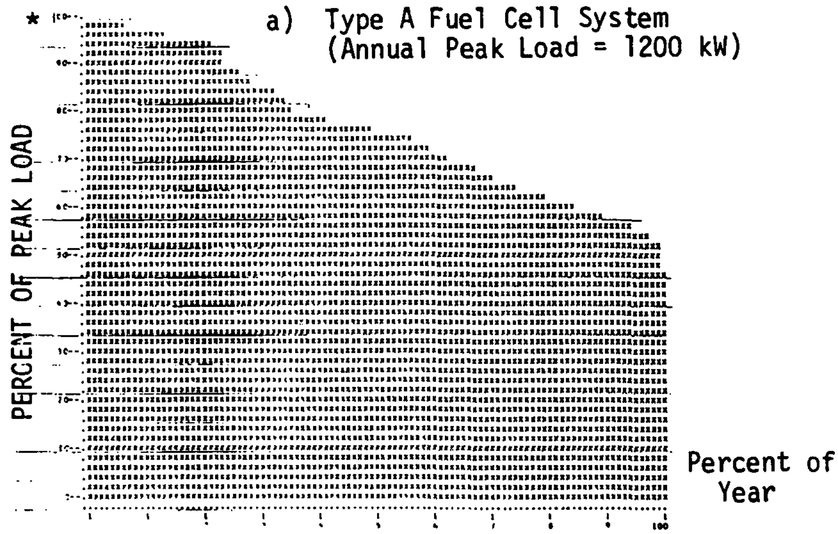


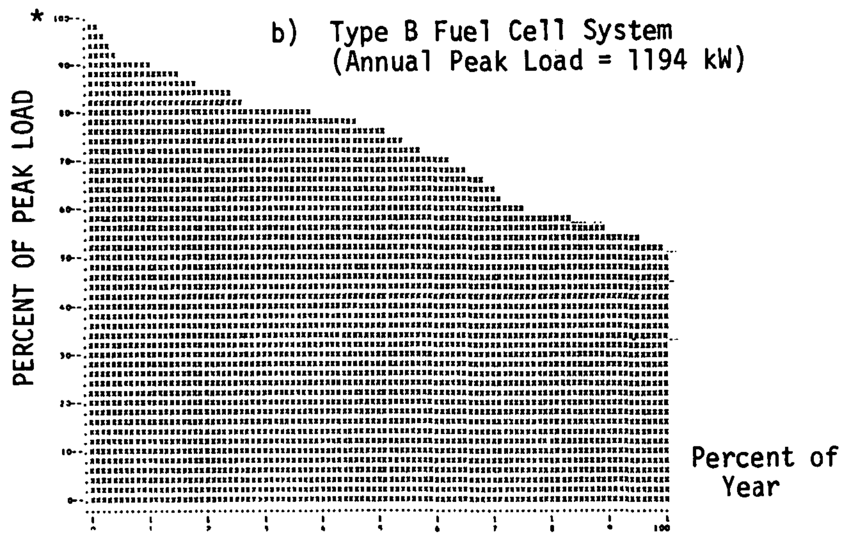
Figure G-8 Annual Load Duration Curve for Hospital
Chicago

* 100% = 1200 kW

a) Type A Fuel Cell System
(Annual Peak Load = 1200 kW)



b) Type B Fuel Cell System
(Annual Peak Load = 1194 kW)



c) Type C Fuel Cell System
(Annual Peak Load = 1147 kW)

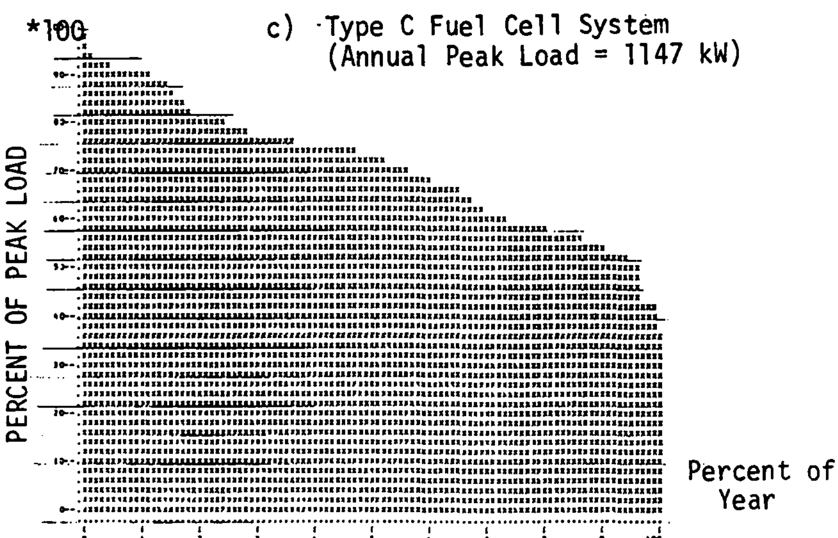


Figure G-9 Annual Load Duration Curve for Hospital, Dallas

* 100% = 1200 kW

APPENDIX H

SAMPLE RELIABILITY CALCULATION

APPENDIX H

SAMPLE RELIABILITY CALCULATION

H.1 Service Reliability Index

A loss of energy probability measure was selected for this study of on-site fuel cell systems because such systems could presumably meet some fraction of the building's electrical load even when one or more of the total number of fuel cell modules was out of service. Specifically, a percent service reliability index (SRI) was calculated as:

$$\mathrm{SRI} = \frac{\text{Annual Energy Demand-Annual Demand Not Served}}{\text{Annual Energy Demand}} \times 100\% \qquad \text{(H-1)}$$

For this study, the value of SRI, thus calculated, was required to be approximately equal to (but not less than) 99.88 percent.

H.2 OS/IES vs. Conventional Supply Reliability Assessment

Since an on-site fuel cell system with a utility grid tie-in would automatically provide the customer with service reliability at least equal to that provided by conventional utility services, the reliability evaluation for comparison purposes applies only to the on-site fuel cell system options with no utility tie-in.

The method that was used is an adaptation of conventional utility loss-of-energy approaches, and relates the probabilities of operation in various fuell cell supply system capacity states to the annual load shape reflected at the fuel cell to determine the probabilistic magnitude of the annual energy requirement not served. Fuel cell system designs were then adjusted by adding or removing fuel cell modules until the reliability margin equaled that of the conventional utility supply. It was assumed that the fuel cell power plant design consisted of a discrete number of identical fuel cell modules of equal capacity. The fuel cell module forced outage rate was three percent.

A fuel cell electrical (output) load duration curve for each building application was the main input to the calculation procedure.

The following simple example illustrates the reliability calculation methodology. Figure H-1 represents three 300 kW fuel cell modules each with an assumed three percent forced outage rate. Also shown are the calculated probabilities for existence of various capacity states. Figures H-2 and H-3 show a hypothetical building daily load shape and associated load duration curve, respectively.

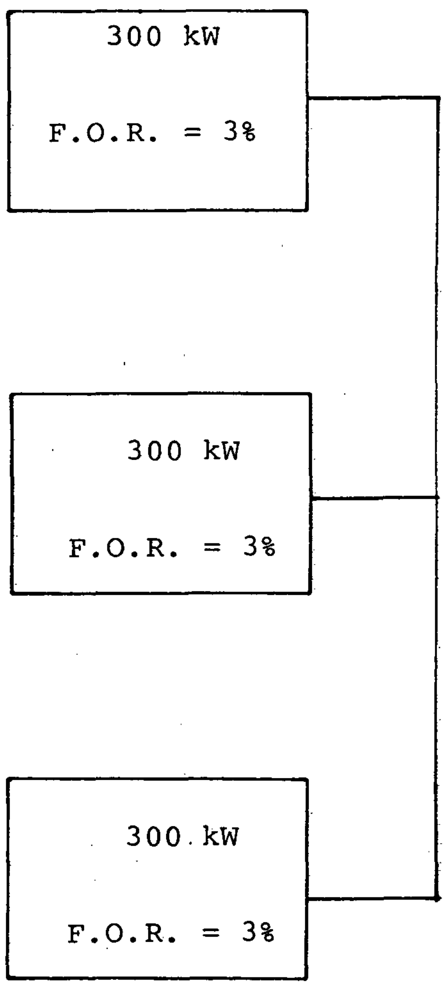
Table H-1 shows the calculation of probabilistic energy (kW-hr) lost (or not served) by the fuel cell supply system in serving the 24-hour building load demand. As the table shows, this requires determination of:

i) the various capacity states;
ii) the energy lost if each capacity state existed throughout the entire 24-hour period (area under load curve or load duration curve bordered by the respective capacity state);
iii) the probability that each capacity state will exist at any time throughout the 24-hour period;
iv) the probabilistic energy lost (B x C), or not served in a 24-hour period for each capacity state; and
v) the total energy not served for all possible capacity states.

The reliability calculations performed in this study need the annual load duration curves presented in Appendix G.

FIGURE H-1

FUEL CELL SYSTEM CAPACITY STATES



CAPACITY STATE PROBABILITIES

*P(900) = (.97)(.97(.97) = .912673

P(600) = (.97)(.97)(.03)3 = .084681

P(300) = (.97)(.03)(.03)3 =.002619

P(0) = (.03)(.03)(.03) = .000027

1.000000

*P(x) = Probability of x-kW available fuel cell capacity.

FIGURE H-2

BUILDING 24 - HOUR LOAD SHAPE

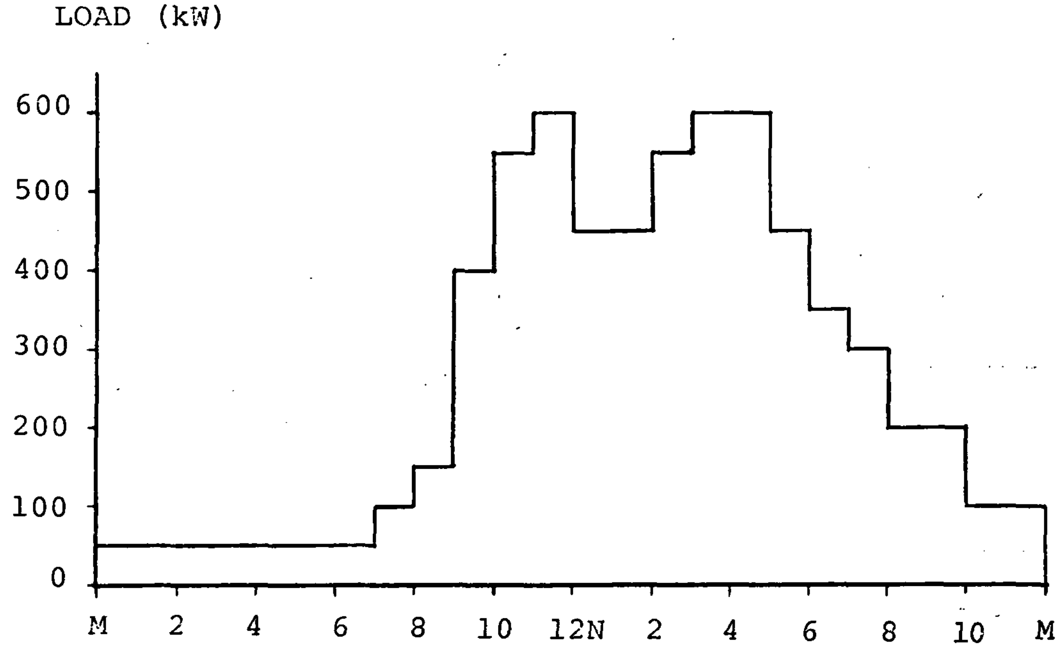


FIGURE H-3

BUILDING LOAD DURATION CURVE

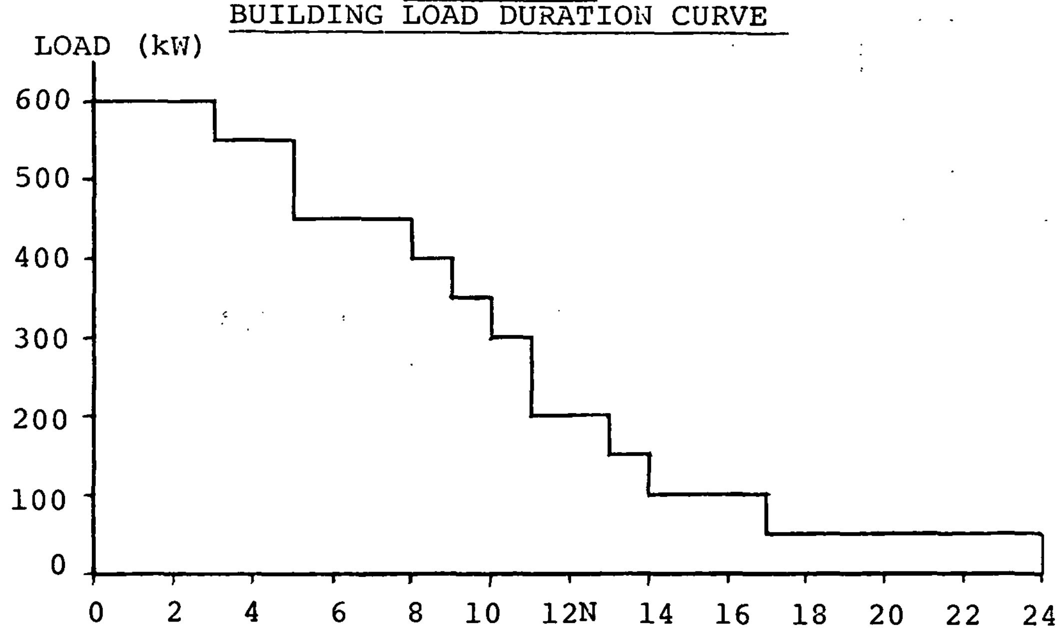


TABLE H-1

LOSS-OF-ENERGY PROBABILITY CALCULATION

(A) CAPACITY AVAILABILITY STATE	(B) ENERGY LOST IF AT STATE (A) ALWAYS*	(C) PROBABILITY OF STATE (A)	(D) PROBABILISTIC ENERGY LOST IN SERVING 24-HOUR LOAD
(kW)	(kW-Hrs)		(kW-Hrs)
900	0	.912673	0
600	0	.084681	0
300	2000	.002619	5.238
0	6500	.000027	.176

Total Energy Demand Not Served = 5.414 kWh
(sum of entries in Column D)

Loss of Energy Probability = $\frac{6500-5.414}{6500}$ x 100% = 99.917%

* Area under load duration curve but above capacity stated in Column A.

APPENDIX I

FUEL CELL SYSTEM EQUIPMENT LISTS

TABLE I-1

FUEL CELL SYSTEM EQUIPMENT LIST

LOW-RISE APARTMENT BUILDING

EQUIPMENT ITEM	LOCATION					
	CHICAGO		WASHINGTON		DALLAS	
	QTY	SIZE	QTY	SIZE	QTY	SIZE
Type A Fuel Cell	12	6 kW_e	12	6 kW_e	12	6 kW_e
Electric Vapor Compression Chiller	1	70.4 kW_t	1	70.4 kW_t	1	70.4 kW_t
Absorption Chiller	1	88.0 kW_t	1	106 kW_t	1	106 kW_t
Air/Water Heat Pump	1	29.3 kW_t	1	29.3 kW_t	1	14.7 kW_t
Electric Resistance Space Heater	1	20 kW_e	1	20 kW_e	1	20 kW_e
Supplemental Package Boiler	1	88.0 kW_t	1	88.0 kW_t	1	88.0 kW_t
Type B Fuel Cell	12	6 kW_e	12	6 kW_e	12	6 kW_e
Electric Vapor Compression Chiller	1	70.4 kW_t	1	70.4 kW_t	1	70.4 kW_t
Absorption Chiller	1	88.0 kW_t	1	106 kW_t	1	106 kW_t
Air/Water Heat Pump	1	29.3 kW_t	1	29.3 kW_t	1	14.7 kW_t
Electric Resistance Space Heater	1	20 kW_e	1	20 kW_e	1	20 kW_e
Supplemental Package Boiler	1	88.0 kW_t	1	88.0 kW_t	1	88.0 kW_t
Type C Fuel Cell	12	6 kW_e	12	6 kW_e	12	6 kW_e
Electric Vapor Compression Chiller	1	70.4 kW_t	1	70.4 kW_t	1	70.4 kW_t
Absorption Chiller	1	88.0 kW_t	1	106 kW_t	1	106 kW_t
Air/Water Heat Pump	1	29.3 kW_t	1	29.3 kW_t	1	14.7 kW_t
Electric Resistance Space Heater	1	20 kW_e	1	20 kW_e	1	20 kW_e
Supplemental Package Boiler	1	88.0 kW_t	1	88.0 kW_t	1	88.0 kW_t

TABLE I-2

FUEL CELL SYSTEM EQUIPMENT LIST

RETAIL STORE

EQUIPMENT ITEM	LOCATION					
	CHICAGO		WASHINGTON		DALLAS	
	QTY	SIZE	QTY	SIZE	QTY	SIZE
Type A Fuel Cell	12	60 kW_e	11	67 kW_e	12	61 kW_e
Electric Vapor Compression Chiller	1	352 kW_t	1	352 kW_t	1	352 kW_t
Absorption Chiller	1	880 kW_t	1	880 kW_t	1	880 kW_t
Air/Water Heat Pump	1	88.0 kW_t	1	88.0 kW_t	1	88.0 kW_t
Electric Resistance Space Heater	1	40 kW_e	1	40 kW_e	1	40 kW_e
Supplemental Package Boiler	1	235 kW_t	1	235 kW_t	1	235 kW_t
Type B Fuel Cell	13	55 kW_e	12	61 kW_e	12	61 kW_e
Electric Vapor Compression Chiller	1	352 kW_t	1	352 kW_t	1	352 kW_t
Absorption Chiller	1	880 kW_t	1	880 kW_t	1	880 kW_t
Air/Water Heat Pump	1	88.0 kW_t	1	88.0 kW_t	1	88.0 kW_t
Electric Resistance Space Heater	1	40 kW_e	1	40 kW_e	1	40 kW_e
Supplemental Package Boiler	1	235 kW_t	1	235 kW_t	1	235 kW_t
Type C Fuel Cell	11	67 kW_e	13	56 kW_e	15	48 kW_e
Electric Vapor Compression Chiller	1	352 kW_t	1	352 kW_t	1	352 kW_t
Absorption Chller	1	880 kW_t	1	880 kW_t	1	880 kW_t
Air/Water Heat Pump	1	88.0 kW_t	1	88.0 kW_t	1	88.0 kW_t
Electric Resistance Space Heater	1	40 kW_e	1	40 kW_e	1	40 kW_e
Supplemental Package Boiler	1	235 kW_t	1	235 kW_t	1	235 kW_t

TABLE I-3

FUEL CELL EQUIPMENT LIST

HOSPITAL

EQUIPMENT ITEM	LOCATION					
	CHICAGO		WASHINGTON		DALLAS	
	QTY	SIZE	QTY	SIZE	QTY	SIZE
Type A Fuel Cell	11	120 kW_e	11	130 kW_e	14	100 kW_e
Electric Vapor Compression Chiller	1	352 kW_t	1	528 kW_t	1	704 kW_t
Absorption Chiller	1	1408 kW_t	1	1232 kW_t	1	1056 kW_t
Air/Water Heat Pump	1	264 kW_t	1	352 kW_t	1	440 kW_t
Electric Resistance Space Heater	1	70 kW_e	1	60 kW_e	1	5 kW_e
Supplemental Package Boiler	1	293 kW_t	1	293 kW_t	1	293 kW_t
Type B Fuel Cell	14	100 kW_e	14	100 kW_e	10	140 kW_e
Electric Vapor Compression Chiller	1	528 kW_t	1	704 kW_t	1	528 kW_t
Absorption Chiller	1	1232 kW_t	1	1056 kW_t	1	1232 kW_t
Air/Water Heat Pump	1	352 kW_t	1	440 kW_t	1	352 kW_t
Electric Resistance Space Heater	1	60 kW_e	1	45 kW_e	1	60 kW_e
Supplemental Package Boiler	1	293 kW_t	1	293 kW_t	1	293 kW_t
Type C Fuel Cell	11	120 kW_e	11	130 kW_e	10	140 kW_e
Electric Vapor Compression Chiller	1	352 kW_t	1	528 kW_t	1	528 kW_t
Absorption Chiller	1	1408 kW_t	1	1232 kW_t	1	1232 kW_t
Air/Water Heat Pump	1	264 kW_t	1	352 kW_t	1	381 kW_t
Electric Resistance Space Heater	1	70 kW_e	1	60 kW_e	1	None Required
Supplemental Package Boiler	1	293 kW_t	1	293 kW_t	1	293 kW_t

APPENDIX J

ECONOMIC ANALYSIS METHODOLOGY

APPENDIX J

ECONOMIC ANALYSIS METHODOLOGY

The primary economic parameter calculated for this study was the levelized annual cost of the respective conventional and fuel cell energy systems.

This levelized annual cost is defined as the minimum constant net revenue required each year of the life of the energy system to cover all expenses, the cost of money, and the recovery of the initial investment. This is the capital investment analysis approach commonly used by electric utilities; however, the methodology is equally applicable to other investments.

The levelized annual cost was computed as follows:

$$\begin{aligned}\text{levelized annual cost} &= \text{levelized fixed charges}\\ &\quad + \text{levelized operating costs}\\ &\quad - \text{levelized revenue}\end{aligned}$$

(The only revenues that were considered here were those from the sale of electric power to the utility as discussed in Section 7.2 of this report.)

J.1 Applicability of the Method

Comparing two investment alternatives on the basis of minimum cost is meaningful provided that revenues are unaffected by the investment. In that case, the minimum cost system will maximize profits. The assumption that revenues are unaffected is valid for many capital investments. Even where revenues do change as a result of the investment, the method can be employed provided the change in revenues is small, and can be predicted with reasonable certainty. In this case, revenues can be credited against costs to arrive at a net cost.

Inherent in the method are several other assumptions, all of which must be satisfied if the method is to be employed. These are:

(a) the investment is made at the start of the service life;

(b) the investing organization can be treated as a limitless pool of money with unchanging ratio of debt to equity;

(c) cost of debt, cost of equity, and tax rates are constant throughout the service life; and

(d) the investing organization pays sufficient income tax each year to take full advantage of the investment tax credit.

J.2 Groundrules

The following general groundrules or assumptions were applied to all economic analyses:

(a) general inflation (i.e., the change in the value of the dollar) was assumed to be zero;

(b) real escalation rates (i.e., changes in costs of specific items higher or lower than the change in value of the dollar) were explicitly accounted for;

(c) income taxes were included in the analysis;

(d) investment tax credit was included in the analysis and was treated as a reduction in first year's taxes;

(e) other taxes were assumed to be a percentage of the capital investment in the first year;

(f) insurance costs were assumed to be a percentage of the capital investment in the first year;

(g) insurance costs and other taxes were assumed not to escalate;

(h) salvage or residual values were assumed to be zero;

(i) cost increases during construction (due to capital cost escalation and cost of capital) were included in the analysis;

(j) load factors and capacity factors were held constant throughout the economic life of the investment and were assumed to be an average annual value;

(k) the value of the cost of capital used in the analysis was consistent with the assumption of zero inflation; and

(l) the after-tax cost of capital was defined as:

$$m = (1-t) \cdot f_D i_D + f_C i_C$$

where f_D = ratio of debt capital to total capital

f_C = ratio of common equity capital to total capital

i_D, i_C are the costs of debt and common equity assuming zero inflation, respectively

t = composite federal, state, and local income tax rate.

(m) retirement dispersion was neglected;

(n) flow-through accounting was assumed throughout;

(o) the levelized cost computed was the net cost (i.e., the gross levelized cost less credit for revenues that result from the investment, such as sales of electric power to the utility grid;

(p) net levelized cost was expressed in reference-year dollars;

(q) since the purpose of this analysis was to determine the net energy <u>cost</u>, the <u>cost</u> of capital (and not the desired rate of return) was used in the analysis;

(r) capital cost escalation was assumed zero;

(s) state and local taxes and insurance were assumed to be a fixed percentageof the capital investment, C;

(t) straight-line book and tax depreciation were assumed in all cases; and

(u) the magnitude of the capital investment at time zero was equal to the capital cost estimate in constant year dollars adjusted for cost increases during construction as described below.

Let K be the capital cost estimate (as distinct from expenditure or investment) of the energy system to be expressed in constant year dollars. K does not include interest or escalation during construction or working capital. The C, the capital cost expenditure used in the rate of return analysis, was defined as follows:

$$C = k_m \cdot K \tag{J-1}$$

where

$$k_m = \text{cost of capital factor} = e^{0.418mL} \tag{J-2}$$

K = capital cost without cost of capital or escalation during construction

L = design and construction time, years

(v) the levelized fixed LFC was computed as follows:

$$LFC = C \cdot FCR \qquad \text{(J-3)}$$

where

FCR = fixed charge rate

C = capital investment as defined in equation J-1

(w) the fixed charge rate FCR was computed using the following equations (reference 1, Appendix E):

$$FCR = \left(\frac{CRF_{m,n_B}}{(1-t)}\right) \left(1 - t \cdot (DEP) - c\right) \qquad \text{(J-4)}$$

CRF_{m,n_B} = capital recovery factor for the after-tax cost of capital m and the economic life n_B

t = tax rate

c = investment tax credit rate

DEP = levelized depreciation factor, as defined below

m = after-tax cost of capital at the assumed inflation rate

The term DEP is given by:

$DEP = 1/n_T CRF_{m,n_B}$ for straight-line depreciation (J-5)

(x) expenditures and revenues occurring over the economic life of the investment was levelized as follows. For costs (or revenues) that vary at a constant annual rate:

$$LC = P_o \cdot (CFR_{m,n}/CRF_{k,n}) \qquad \text{(J-6)}$$

where

P_o = the cost (or revenue) in year j = 0

$$k = (1 + m)/(1 + e_p + i_o) - 1 \qquad (J\text{-}7)$$

e_p = constant annual escalation rate

i_o = constant annual inflation rate

For costs that are constant no levelizing is necessary.

References

1. "The Cost of Energy From Utility-Owned Solar Electric Systems," J.W. Doane, *et al.*, JPL 5040-29, ERDA/JPL-1012-76/3, June 1976.

2. "The Discounted Cash Flow (DCF) and Revenue Requirement (RR) Methodologies in Energy Cost Analysis," Doan L. Phung, Institute for Energy Analysis, Oak Ridge Associated Universities (ORAU/IEA-78-18(R), September 1978).

APPENDIX K

PACIFIC GAS AND ELECTRIC COMPANY'S
RATE SCHEDULE FOR STANDBY SERVICE

Schedule No. S-1

STAND-BY SERVICE

APPLICABILITY

This schedule is applicable to stand-by or breakdown service to customers whose premises are regularly supplied, in whole or in part, with electric energy from a privately owned source of supply; to auxiliary service to customers who at times take service (by means of a double-throw switch) from another public Utility; and to other electric service where the Utility must provide reserve capacity and stand ready at all times to supply electricity, but where the use of electric service is not of a usual, regular or continuous character.

TERRITORY

The entire territory served.

RATES

	Per Meter Per Month
Customer Charge in addition to any other Customer Charge	$5.00
Stand-by Charge per kw of Contract Capacity: (Subject to voltage adjustment as provided in Special Condition 11)	
Where customer's plant or other source employs Co-generation Technology or utilizes Renewable Resources as the energy source (as defined in Special Condition 13)	0.75
All other service	0.95
Stand-by Charge per kw of Contract Capacity, excess off peak service (Subject to voltage adjustment as provided in Special Condition 11)	0.40
Reactive Demand Charge (in addition to Stand-by Charge) per kvar of maximum reactive demand	0.15

Demand and Energy Charges (in addition to Stand-by Charge):

The Regular Schedule Applicable (see Special Condition 1) including the Customer Charge, if any, the minimum charges, Energy Cost Adjustment, Fuel Collection Balance Adjustment, and all other provisions of said schedules.

SPECIAL CONDITIONS

1. **Regular Schedule Applicable:** Stand-by service, either alone or in combination with other load through the same meter, shall be billed in conjunction with that rate schedule which would be applicable to customer's total load including that portion of customer's load for which stand-by service is provided

2. **Allowance For Customer's Plant Maintenance:** After a customer has been connected to Utility's system under this schedule and its plant has been in operation for a period of six months, for that portion of the Contract Capacity that may be out of service for scheduled maintenance in the months of February, March, April and/or November, such outages up to 30 consecutive days per calendar year will be ignored for the purposes of determining demand charges under the Regular Schedule Applicable. This allowance shall be made only if the customer submits to the Utility (a) 90 days' prior notice of intent to perform maintenance and (b) records showing to the satisfaction of the Utility what part of the load on the Utility's system in any of the aforementioned months was due to such scheduled maintenance. The Utility, at its sole option, may defer customer's scheduled maintenance subsequent to which deferral an outage for maintenance will be allowed in accordance herewith. Notice of such deferral, if any, shall be given by the Utility not less than 60 days prior to customer's scheduled outage, except in event of an emergency. Where maintenance is performed during a part of one or more of these months, this provision shall apply only during that part. One allowance each calender year for a partial outage for maintenance for each unit of a multiple unit source or pair of outages of up to 72 hours, for each of one or more units, to remove and replace all or a portion of customer's source shall be made in accordance with the foregoing during the months specified.

(continued)

Schedule No. S-1

STAND-BY SERVICE

(Continued)

3. **Experimental Allowance For Unconventional Generation:** Regardless of other stand-by requirements and charges therefore, there shall be no customer or stand-by charges hereunder for any class of service for up to 300 kw of unconventional generation. Unconventional generation is electric generation by wind power; solar heat, either direct conversion or steam; steam where the energy source is rubbish, animal waste or other waste fuel not a fossil fuel or a derivation thereof; tidal or wave energy; geothermal energy; and such other sources as the Utility may permit for this allowance from time to time. Service under this allowance is subject to all other applicable provisions of this schedule and tariff, including a service contract. This special condition is experimental and its application may be terminated by the Utility at its sole option at any time. Upon notice to customers of such termination, this special condition will remain in effect as to customers then served hereunder for a period of 60 calendar months thereafter.

4. **Parallel Operation:** Any customer served hereunder may operate its generating plant in parallel with Utility's system if customer's plant is constructed and operated in accordance with Utility's requirements. However, a customer who operates its plant in parallel must assume responsibility for protecting the Utility and other parties from damage resulting from negligent operation of the customer's facilities, except where the damage results from the Utility's requirements. The Utility will provide at its expense the normal metering equipment for the size and type of load served. The Utility will provide at the customer's expense other metering equipment on both the service and the alternate source as determined to be necessary by the Utility. Meters installed hereunder shall not allow reverse registration.

5. **Circuit Breaker Setting:** Where a circuit breaker is used to limit the maximum load upon the Utility's system, the Contract Capacity may be based upon the setting of such circuit breaker, in which case it will be 80% of the load in kva at which the circuit breaker will open instantaneously. Such circuit breaker setting will not be reduced during the contract period, but may be increased upon request of the customer and the signing of a new 3-year contract.

6. **Demand:** When the Utility's service is used for stand-by (either alone or in combination with other load through the same meter) and the customer submits to the Utility records showing to the satisfaction of the Utility what part of the load on the Utility's system in any month was due to scheduled shutdown, forced shutdown or failure of customer's plant (or other source) or a portion thereof for which a stand-by charge is being paid, then the Contract Capacity used to determine charges hereunder in that month will be reduced by a number of kilowatts equal to the number of kilowatts of metered demand caused by such shutdown or failure and for which a demand charge under the Regular Schedule Applicable (in excess of the stand-by charge) is paid in that month. Increases in metered demand resulting from abnormal Utility system operation will be ignored for the purpose of determining demand charges under the Regular Schedule Applicable during the first hour after the event causing such demand.

7. **Contract:** This schedule is applicable only on a 3-year contract when stand-by service is first rendered in any instance and year by year thereafter. If the customer at any time increases the capacity of the customer's plant (or other source) or increases the connected load served therefrom, the customer shall promptly so notify the Utility and the Contract Capacity shall be redetermined under the provisions of Special Condition 8 below to be applicable for the month in which such increase occurs and thereafter for so long as such contract shall remain in force or until such contract is again changed in accordance with the provisions hereof.

8. **Limitation on Contract Capacity Served:** Stand-by service to new or increased loads is limited to the Utility's ability to serve such loads without jeopardizing service to existing customers on rate schedules providing for firm service, including stand-by service. In the event stand-by service to any load or combination of loads is refused by the Utility, the Utility shall notify the Public Utilities Commission of the State of California (Commission) in writing, setting forth for the full particulars of the matter. Stand-by service to any installation of over 25,000 kilowatts or of an unusual character will require a special contract which shall be subject to approval of the Commission.

9. **Contract Capacity:** The Contract Capacity to be used for billing under the above rates shall be as set forth in the customer's contract for service. For new or revised contracts under Special Condition 7 above, the Contract Capacity shall be numerically equal to the lesser of (a) the normal rated capacity of the customer's generating facilities at unity power factor plus similarly rated capacity from any source other than the Utility's system, (b) the maximum amount of connected load in kva which can be served simultaneously from the customer's generating plant plus capacity from any source other than the Utility's system, or (c) 80% of the circuit breaker setting as provided under Special Conditon 5 above.

(continued)

Schedule No. S-1

STAND-BY SERVICE

(Continued)

10. **Reactive Demand:** When the customer's plant (or other source) is operated in parallel with the Utility's system, the customer will so design and operate his facilities that the reactive current requirements of the portion of the customer's load supplied from the customer's plant (or other source) are not supplied at any time from the Utility's system. In the event customer places a reactive demand on the Utility in any month in excess of 0.1 kvar per kw of Contract Capacity, the Reactive Demand Charge shall be effective that month and each month thereafter until the customer demonstrates to the Utility's satifaction that adequate correction has been provided.

11. **Voltage Adjustment:** The above stand-by charges are applicable without adjustment for voltage when delivery is made at transmission voltage (60 kv and above). When delivery is made at the standard primary distribution voltage at 2 kv or above available in the area from the Utility's distribution line or, where the Utility has elected to supply service at a standard primary distribution voltage from a transmission line, for its operating convenience, from Utility-owned transformers on the customer's property, the above charges for any month will be increased by 10¢ per kw of contract capacity. When (a) delivery is made at less than 2 kv, or (b) when delivery is made by means of Utility-owned transformers at a distribution voltage other than a standard primary distribution voltage, or (c) when delivery is made at a voltage that requires more than one stage of transformation from transmission voltage, the above charges for any month will be increased by 25¢ per kw of contract capacity.

The Utility retains the right to change its line voltage at any time, after reasonable advance notice to any customer affected by such change, and such customer then has the option to change his system so as to receive service at the new line voltage or to accept service through transformers to be supplied by Utility subject to the voltage adjustment above.

12. **Excess Off Peak Service:** Excess off peak stand-by service is available only where the Regular Schedule Applicable is Schedule No. A-22 or A-23 and applies to service which is provided only during the off peak periods specified therein and which is in excess of other stand-by service, if any.

13. **Definitions:**

(a) Co-generation Technology — the use for the generation of electricity of exhaust steam, waste steam, heat, or resultant energy from an industrial, commercial, or manufacturing plant or process, or the use of exhaust steam, waste steam, or heat from a thermal powerplant for an industrial, commercial, or manufacturing plant or process.

(b) Renewable Resources — those sources of energy which are not diminished by use for electric generation, including wind power; solar heat, either direct conversion or steam; steam where the energy source is rubbish, animal waste or other waste fuel not a fossil fuel or a derivation thereof; tidal or wave energy; and geothermal energy. The use of renewable resources may or may not employ Co-generation Technology.

APPENDIX L

BASE CASE NUMERICAL RESULTS

Table L-1

LEVELIZED ANNUAL COSTS: LOW-RISE APARTMENT BUILDING

(1978 Dollars)

	Cost Item	Conventional System		Fuel Cell Type		
		All-Electric	Gas & Electric	A	B	C
WASHINGTON	Fixed Charge	2,777	2,661	10,487	9,859	9,646
	Gas	---	6,255	16,976	13,912	16,101
	Purchased Power	26,952	15,580	---	---	---
	O&M	1,920	4,128	6,456	6,483	6,358
	Insurance & Local Taxes	1,548	1,483	5,845	5,495	5,377
	TOTAL	33,197	30,107	39,763	35,750	37,482
CHICAGO	Fixed Charge	2,777	2,661	10,202	9,575	9,375
	Gas	---	7,551	16,065	12,988	15,110
	Purchased Power	27,277	14,857	---	---	---
	O&M	1,920	4,128	5,974	5,975	5,849
	Insurance & Local Taxes	1,548	1,483	5,687	5,337	5,225
	TOTAL	33,522	30,680	37,928	33,875	35,559
DALLAS	Fixed Charge	2,777	2,661	10,247	9,627	9,420
	Gas	---	5,393	17,545	14,267	16,653
	Purchased Power	29,798	19,088	---	---	---
	O&M	1,920	4,128	6,477	6,444	6,325
	Insurance & Local Taxes	1,548	1,483	5,712	5,366	5,251
	TOTAL	36,043	32,753	39,981	35,703	37,648

Table L-2

LEVELIZED ANNUAL COSTS: RETAIL STORE

(1978 Dollars)

	Cost Item	Conventional System		Fuel Cell Type		
		All-Electric	Gas & Electric	A	B	C
WASHINGTON	Fixed Charge	13,522	8,941	35,478	30,130	28,421
	Gas	---	14,240	117,762	102,009	111,829
	Purchased Power	156,197	104,985	---	---	---
	O&M	15,000	8,970	26,790	26,550	26,090
	Insurance & Local Taxes	7,525	4,975	19,743	16,767	15,816
	TOTAL	192,244	142,111	199,772	175,456	182,156
CHICAGO	Fixed Charge	18,714	10,162	35,146	29,727	28,278
	Gas	---	14,244	111,148	95,877	106,178
	Purchased Power	148,663	94,070	---	---	---
	O&M	15,000	8,970	26,380	26,110	25,580
	Insurance & Local Taxes	10,414	5,655	19,558	16,543	15,736
	TOTAL	192,790	133,102	192,233	168,256	175,772
DALLAS	Fixed Charge	13,522	9,149	35,543	30,299	28,772
	Gas	---	9,268	130,868	114,836	122,732
	Purchased Power	168,400	121,567	---	---	---
	O&M	15,000	8,970	27,300	27,140	26,780
	Insurance & Local Taxes	7,525	5,091	19,779	16,861	16,011
	TOTAL	204,447	154,045	213,490	189,135	194,295

Table L-3

LEVELIZED ANNUAL COSTS: HOSPITAL
(1978 Dollars)

	Cost Item	Conventional System		Fuel Cell Type		
		All-Electric	Gas & Electric	A	B	C
WASHINGTON	Fixed Charge	20,785	12,725	47,042	39,788	36,530
	Gas	---	204,035	347,431	257,367	302,782
	Purchased Power	670,121	256,660	---	---	---
	O&M	25,200	18,060	66,140	67,450	64,260
	Insurance & Local Taxes	2,106	1,289	4,766	4,031	3,701
	TOTAL	718,212	492,769	465,379	368,637	407,273
CHICAGO	Fixed Charge	19,262	12,075	43,235	39,438	34,007
	Gas	---	188,163	338,074	272,209	289,916
	Purchased Power	697,929	253,960	---	---	---
	O&M	25,200	18,060	64,380	67,520	63,330
	Insurance & Local Taxes	1,952	1,223	4,381	3,996	3,446
	TOTAL	744,343	473,481	449,969	383,164	390,699
DALLAS	Fixed Charge	21,039	12,725	48,021	38,570	36,124
	Gas	---	227,495	358,160	287,818	306,412
	Purchased Power	622,151	260,436	---	---	---
	O&M	25,200	18,060	67,270	64,830	63,120
	Insurance & Local Taxes	2,132	1,289	4,866	3,908	3,660
	TOTAL	670,522	520,005	478,317	395,127	409,316

Table L-4

ANNUAL ENERGY CONSUMPTION: LOW-RISE APARTMENT BUILDING

	Type of Energy	Conventional System		Fuel Cell Type		
		All-Electric	Gas & Electric	A	B	C
WASHINGTON	Gas Consumption, 10^6 kJ	---	1,473	3,997	3,276	3,791
	Purch. Electricity, 10^6 kWh	591.6	342.0	---	---	---
	Purch. Electricity, 10^6 kJ	2,132	1,233	---	---	---
	Equiv. Res. Electricity, 10^6 kJ	6,580	3,804	---	---	---
	TOTAL Energy, 10^6 kJ	6,581	5,277	3,997	3,276	3,791
CHICAGO	Gas Consumption, 10^6 kJ	---	1,778	3,783	3,058	3,558
	Purch. Electricity, 10^6 kWh	598.8	3,261	---	---	---
	Purch. Electricity, 10^6 kJ	2,158	1,175	---	---	---
	Equiv. Res. Electricity, 10^6 kJ	6,661	3,627	---	---	---
	TOTAL Energy, 10^6 kJ	6,661	5,406	3,783	3,058	3,558
DALLAS	Gas Consumption, 10^6 kJ	---	1,270	4,131	3,359	3,921
	Purch. Electricity, 10^6 kWh	654.1	419.0	---	---	---
	Purch. Electricity, 10^6 kJ	2,357	1,510	---	---	---
	Equiv. Res. Electricity, 10^6 kJ	7,276	4,660	---	---	---
	TOTAL Energy, 10^6 kJ	7,276	5,930	4,131	3,359	3,921

Table L-5

ANNUAL ENERGY CONSUMPTION: STORE

	Type of Energy	Conventional System		Fuel Cell Type		
		All-Electric	Gas & Electric	A	B	C
WASHINGTON	Gas Consumption, 10^6 kJ	---	2,878	31,024	26,891	29,458
	Purch. Electricity, 10^6 kWh	3,395	2,802	---	---	---
	Purch. Electricity, 10^6 kJ	12,235	10,095	---	---	---
	Equiv. Res. Electricity, 10^6 kJ	37,762	31,158	---	---	---
	TOTAL Energy, 10^6 kJ	37,762	34,037	31,024	26,891	29,458
CHICAGO	Gas Consumption, 10^6 kJ	---	3,271	29,283	25,256	27,974
	Purch. Electricity, 10^6 kWh	3,231	2,566	---	---	---
	Purch. Electricity, 10^6 kJ	11,643	9,249	---	---	---
	Equiv. Res. Electricity, 10^6 kJ	35,936	28,546	---	---	---
	TOTAL Energy, 10^6 kJ	35,936	31,817	29,283	25,256	27,974
DALLAS	Gas Consumption, 10^6 kJ	---	2,376	34,482	30,258	32,333
	Purch. Electricity, 10^6 kWh	3,674	3,162	---	---	---
	Purch. Electricity, 10^6 kJ	13,240	11,395	---	---	---
	Equiv. Res. Electricity, 10^6 kJ	40,865	35,171	---	---	---
	TOTAL Energy, 10^6 kJ	40,865	37,547	34,482	30,258	32,333

Table L-6

ANNUAL ENERGY CONSUMPTION: HOSPITAL

City	Type of Energy	Conventional System		Fuel Cell Type		
		All-Electric	Gas & Electric	A	B	C
WASHINGTON	Gas Consumption, 10^6 kJ	---	75,688	90,964	67,383	79,271
	Purch. Electricity, 10^6 kWh	14,533	5,714	---	---	---
	Purch. Electricity, 10^6 kJ	52,378	20,594	---	---	---
	Equiv. Res. Electricity, 10^6 kJ	161,659	63,890	---	---	---
	TOTAL Energy, 10^6 kJ	161,659	139,248	90,964	67,383	79,271
CHICAGO	Gas Consumption, 10^6 kJ	---	71,364	88,512	71,264	75,907
	Purch. Electricity, 10^6 kWh	15,132	5,656	---	---	---
	Purch. Electricity, 10^6 kJ	54,538	20,384	---	---	---
	Equiv. Res. Electricity, 10^6 kJ	168,327	62,912	---	---	---
	TOTAL Energy, 10^6 kJ	168,327	134,277	88,512	71,264	75,907
DALLAS	Gas Consumption, 10^6 kJ	---	82,016	93,776	75,351	80,225
	Purch. Electricity, 10^6 kWh	13,487	5,796	---	---	---
	Purch. Electricity, 10^6 kJ	48,609	20,890	---	---	---
	Equiv. Res. Electricity, 10^6 kJ	150,027	64,474	---	---	---
	TOTAL Energy, 10^6 kJ	150,027	146,490	93,776	73,351	80,225

1. Report No. CR-165144	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle STUDY OF FUEL CELL ON-SITE, INTEGRATED ENERGY SYSTEMS IN RESIDENTIAL/COMMERCIAL APPLICATIONS		5. Report Date OCTOBER 1980
		6. Performing Organization Code
7. Author(s) R.A. Wakefield, S.Karamchetty, R.H. Rand, W.S. Ku, and V. Tekumalla		8. Performing Organization Report No. E-FC-002
		10. Work Unit No.
9. Performing Organization Name and Address MATHTECH, Inc. Suite 200, 1611 North Kent Street Arlington, Virginia 22209		11. Contract or Grant No. DEN3-89
		13. Type of Report and Period Covered CONTRACTOR REPORT
12. Sponsoring Agency Name and Address U.S. Department of Energy Office of Coal Utilization Washington, D.C. 20545		14. Sponsoring Agency Code DOE/NASA/0089-80/1

15. Supplementary Notes

Final Report. Prepared under Interagency Agreement DE-AI-03-ET-11272. Project Manager, L. Nichols, Solar and Electrochemistry Division, NASA Lewis Research Center, Cleveland, Ohio 44135

16. Abstract This report describes an assessment of the economic and energy use implications of employing phosphoric acid fuel cells in on-site, integrated energy systems (OS/IES) for residential and commercial buildings. The study differs in several respects from past investigations of fuel cell OS/IES (for buildings) in that: 1) It is not an evaluation of any specific fuel cell, but a comparative assessment of three alternative fuel cell designs that are presently being considered for commercial development; 2) The conventional building energy systems were specified by an architect and engineering firm that routinely designs such systems; 3) It was required that all fuel cell systems provide electric service at a reliability equivalent to that of a typical electric utility.

Three building applications were selected for a detailed study: a low-rise apartment building; a retail store, and a hospital. Building design data were than specified for each applicaiton, based on the design and construction of typical, actual buildings. Finally, a computerized building loads analysis program was used to estimate hourly, end-use load profiles for each building in each of three locations: Washington, D.C.; Chicago, Illinois; and Dallas, Texas.

Conventional and fuel cell-based energy systems were designed and simulated for each building in each location. The conventional systems include both an all-electric system and a gas/electric system. Assuming no tie-in with the utility grid, on-site integrated energy systems were designed to incorporate each of the three fuel cell types, so as to: maximize the use of reject heat; minimize energy system life cycle cost; provide electric utility level reliability; and consider the use of supplemental HVAC equipment.

Based on the results of a computer simulation of each energy system, levelized annual costs and annual energy consumptions were calculated for all systems. For the specific buildings analyzed and the data assumptions made, it was concluded that fuel cell OS/IES's are: clearly economic (from a life-cycle cost standpoint) when used in hospitals; marginally economic when employed in retail stores; and generally not economic when used in small apartment buildings. All three applications resulted in energy consumptions savings of from ten to fifty percent.

Additional analyses also were conducted to assess the impacts of: a tie-in with electric utility grid, both with and without sales to the grid; the use of thermal storage; and the effects of varying certain key assumptions.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Fuel Cells Cogeneration On-Site Integrated Energy Systems Residential/Commercial Energy Use	Unclassified-Unlimited Star Category 44 DOE Category UC-93

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	300	

* For sale by the National Technical Information Service, Springfield, Virginia 22161

☆USGPO: 1980 — 757-072/418